THE UNIVERSITY OF ALBERTA

SOME PHYSICAL PROPERTIES OF PNEUMATICALLY PLACED CONCRETE

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Some Physical Properties Of Pneumatically Placed Concrete", submitted by Carl N. Ellert in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Pneumatically-placed concrete, or shotcrete, has been used extensively for a number of years. In the pneumatic process, the mortar is transported through a hose and projected by an air jet directly onto the surface to which it is to be applied. The force of the air jet compacts the material in place, and the product is usually zero slump concrete. The most commonly known and widely used process is the dry mix or "Gunite" process in which the water is added to the mix at the nozzle. In this testing program, material from a wet mix process (Gun-All) was used for the main investigation.

There are many references to the pneumatic method of placing mortar in the literature, however, most of them refer to the physical properties of the material in general, relative terms: there is a dearth of specific test result data.

The object of this testing program was to investigate the compressive, flexural, steel bond and concrete to concrete bond strengths for various shotcrete mixes. Linear expansion under moist conditions and density values were also determined.

Thirteen mixes were used in the investigation, twelve using a Gun-All machine, and one using a Gunite machine.

Open mesh molds and one sided forms were used to fabricate the test specimens, thus enabling the air jet and rebound sand to escape from the work.

The shotcrete test results obtained indicated that the compressive strength-flexural strength relationship was generally within the range of that for regular concrete. The concrete to concrete bond strength in flexure was on the average two-thirds the flexural strength of comparable monolithic shotcrete. The results indicate that ultimate steel bond strengths of 1000 psi or greater can be obtained with normal shotcrete mixes. The linear expansion under moist conditions was found to be comparable to that of regular concrete.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

TABLE OF CONTENTS - (con't)

TABLE OF CONTENTS - (con't)

TABLE OF CONTENTS - (con't)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (con't)

LIST OF FIGURES (con't)

CHAPTER I

INTRODUCTION

TERMINOLOGY

In this text the term "pneumatically placed concrete" is used in discussing the material and processes involved. Other synonymous or nearly synonymous terms are "pneumatically placed mortar", "shotcrete", "air placed concrete", "gunned concrete", and "Gunite".

The general definition of these terms is best laid out by the American Concrete Institute Standards (1)* which state: "Pneumatically Placed Mortar is mortar which is projected by an air jet directly onto the surface to which it is to be applied, irrespective of the type and manufacture of the mixing and placing apparatus. The force of the jet compacts the mortar in place." The term pneumatically placed

* Numbers in brackets indicate references listed in List of References.

concrete is used in this text instead of pneumatically placed mortar, because varying amounts of 3/8 in. maximum size aggregate are used in some of the tests. "Shotcrete" is the term commonly used by the American Concrete Institute, and "Gunite" is the trade name for a specific dry mix process.

CLASSIFICATION OF DIFFERENT PROCESSES

The processes for producing pneumatically placed concrete may be divided into three classifications. These three types have some common features in that the material is transported through a hose, and then sprayed or shot out of a nozzle. The distinguishing features of the processes are as follows:

TYPE I - The material is mixed dry and transported by compressed air through a hose, with the water for the mix added at the nozzle by the nozzle operator. The product is usually zero slump concrete. Examples of the use of this process is found in "Gunite" and "Bondactor" equipment.

TYPE II - The material is wet mixed, and transported by compressed air through a hose. The product is usually zero slump concrete. An example of the use of this process is found in the "Gun-All" equipment.

TYPE III - The material is wet mixed and pumped by positive displacement, with air being introduced only at the nozzle. The nozzle velocity is considerably lower than Types I and II and wetter material is generally used. An example is found in "Airplaco" equipment.

In the literature and particularly in the A.C.I. literature wherever the reports are sufficiently specific, the references to "pneumatically placed mortar" and "shotcrete" appear to deal with the dry mix process.

This testing program deals mainly with the wet mix process (Type II). Tests were conducted on samples from 12 different mixes using a Gun-All Machine, while one mix was tested using the dry mix process, that is, with a Gunite machine.

HISTORICAL REVIEW

The dry mix or "Gunite" process has been used extensively for a number of years, for concrete repair work, construction of canal linings (2), tunnel linings and swimming pools and other types of construction which would otherwise require difficult formwork (3).

Prior to 1951 the published data on shotcrete consisted mainly of descriptions of construction procedures on various projects. A report by Chadwick (3) in 1947 discussed the advantages and disadvantages of shotcrete in general terms. The lack of specific data, and some conflicting claims were noted by R. A. Spencer (4) in 1950. Mr. Spencer stated that "There seems to be a dearth of accurate information about pneumatically-placed mortar." In 1959, P. J. Fluss (5) again noted the lack of shotcrete information, when he stated, "During a recent survey the writer was appalled by the lack of test data pertaining to pneumatically placed mortar."

The A.C.I. Standard "Recommended Practice for the Application of Mortar by Pneumatic Pressure (A.C.I. 805-51)" is the most comprehensive of the available published shotcrete information. It should be noted that in this Standard the definition of pneumatically placed mortar is, "...irrespective of the type and manufacture of the mixing and placing apparatus." The "General Description" and "Recommended Practice" portions, however refer to the dry mix process specifically. It lists advantages and disadvantages and some of the physical properties of shotcrete in general, relative terms.

In 1960, reports from the A.C.I. Committee 201 Symposium on Restoration of Deteriorated Concrete discussed the pneumatic method. Tuthill (6) advocates caution in the use of the pneumatic method because he considers shotcrete to have high shrinkage and high permeability characteristics. Kulberg (7) cites examples where the pneumatic method has been used extensively for long periods of time with "generally good success". Felt (8) tested concrete to concrete bond by means of a shear test, using shotcrete as one method of application. He gives a specific outline of his testing procedure and test results but does not describe the gunning equipment or shooting procedure used.

PURPOSE OF THIS STUDY

The purpose of this study was to determine some of the physical properties of pneumatically placed concrete in order to obtain data which would be useful in shotcrete design and construction. There are many physical characteristics of shotcrete which have a bearing on its function as an engineering material, such as durability, permeability, shrinkage, elastic and thermal properties, and compressive strength, tensile strength, flexural strength, shear strength and reinforcing steel bond strength. This study was of necessity limited to the investigation of only certain of the properties.

The main objectives of this study were to investigate the compressive, flexural, concrete to concrete bond and reinforcing steel bond strength characteristics for shotcrete, and how these properties are affected by variations in the water-cement ratio, the aggregate-cement ratio with uniform consistency, and the aggregate gradation. A Gun-All machine was used because with it, the amount of water in each mix could be controlled. Secondary objectives were to investigate linear expansion under continuous moist curing conditions and to obtain a limited comparison between the Gun-All strengths and those of one Gunite mix.

Compressive, flexural, and steel bond strength characteristics were chosen for study because of their significance in structural shotcrete. Concrete to concrete bond was investigated because of its significance where shotcrete is applied to old concrete surfaces for restoration. Linear expansion under continuous moist conditions was studied because of its possible effect on structures such as swimming pools and water reservoirs, both of which are frequently fabricated using a shotcrete process.

CHAPTER II

DESCRIPTION OF SHOTCRETE EQUIPMENT AND ITS OPERATION

Gunite equipment, which utilizes the dry mix process, has been in use for a number of years, while the Gun-All Machine with its wet mix process is a more recent development. Descriptions of these two types of equipment which were used in this program are outlined below.

DESCRIPTION OF GUN-ALL MACHINE

The operating principle of the Gun-All Machine used in this testing program is illustrated in FIGURE 1. The figure shows one of the two pressurized mixing chambers which are alternately loaded and shot, providing a continuous operation. During the shooting operation, the rotation of the mixing paddles and the chamber air pressure force the material into the sump at the bottom in intermittent slugs which are carried through the material hose by the large volume of "bottom" air introduced at the sump. The intermittent slugs disperse in the material hose and at the

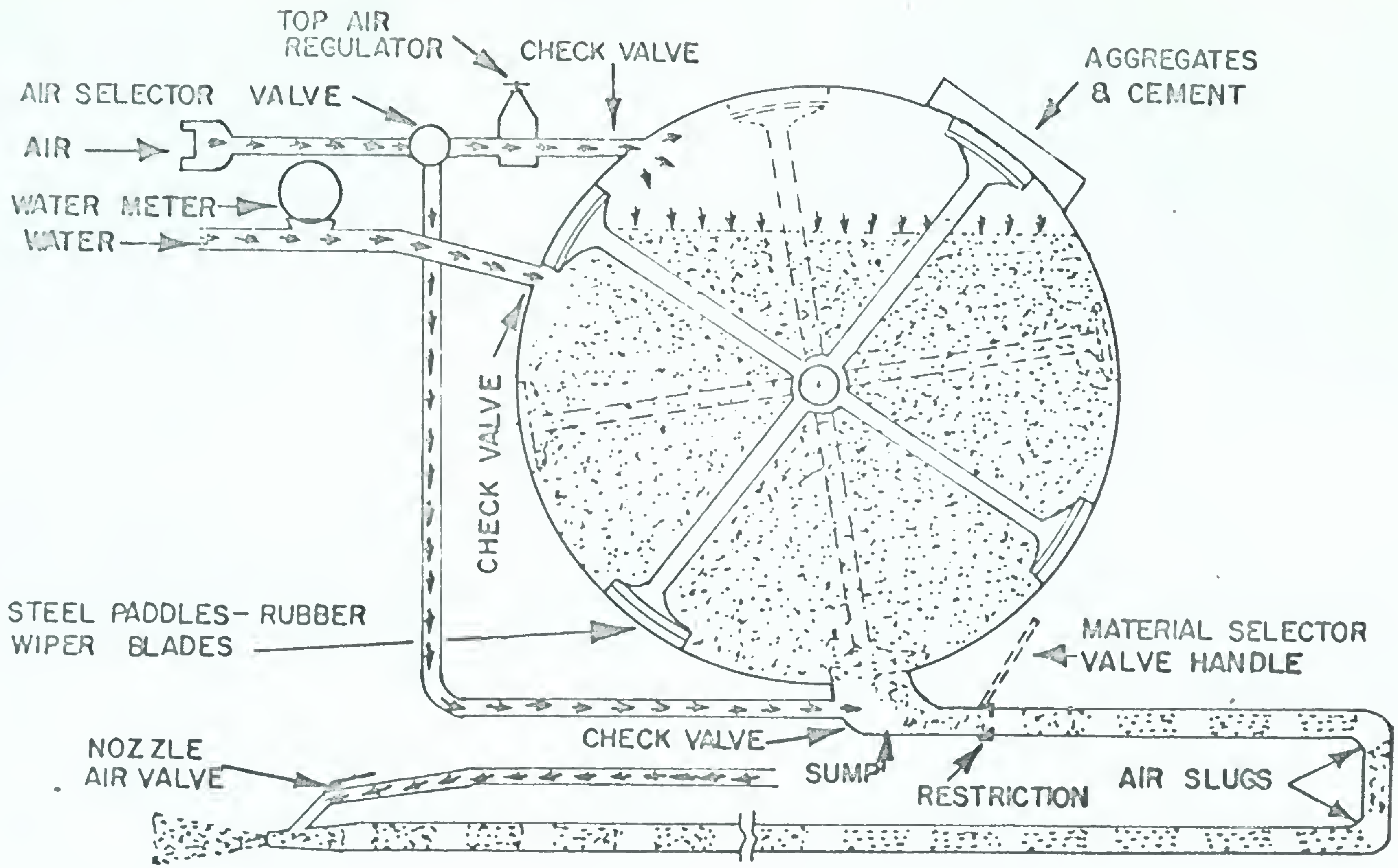


FIGURE NO. I ILLUSTRATION SHOWING OPERATING PRINCIPLE OF GUN-ALL MACHINE

nozzle, where additional air is introduced to increase the exit velocity, the resulting spray from the nozzle is fairly uniform.

The manufacturers rated capacity for a Model D-2 Gun-All Machine is 4 cu yds in place per hour. The air requirements are generally from 125 cfm to 175 cfm, with operating pressures from 50 psi to 90 psi. Aggregates up to 3/8 in. may be used.

The equipment components used in this program included a 125 cfm rotary air compressor, 75 ft of 1-1/4 in. inside diameter material hose, and a rubber lined 3/4 in. inside diameter nozzle. The machine used in this program is shown in FIGURES 2 and 3.

DESCRIPTION OF GUNITE MACHINE

FIGURE 4 shows the operating principle of the Model N-1 Gunite Machine which was used in this program. Dry pre-mixed cement and aggregates (3/8 in. maximum size) are loaded into the upper chamber, and through the use of gates and valves a continuous supply is maintained in the lower chamber under constant pressure. A variable speed motor drives the feed wheel which delivers the material

FIGURE 2

D - 2 Gun-All machine

FIGURE 3

D-2 Gun-All machine being loaded with aggregate on a construction job

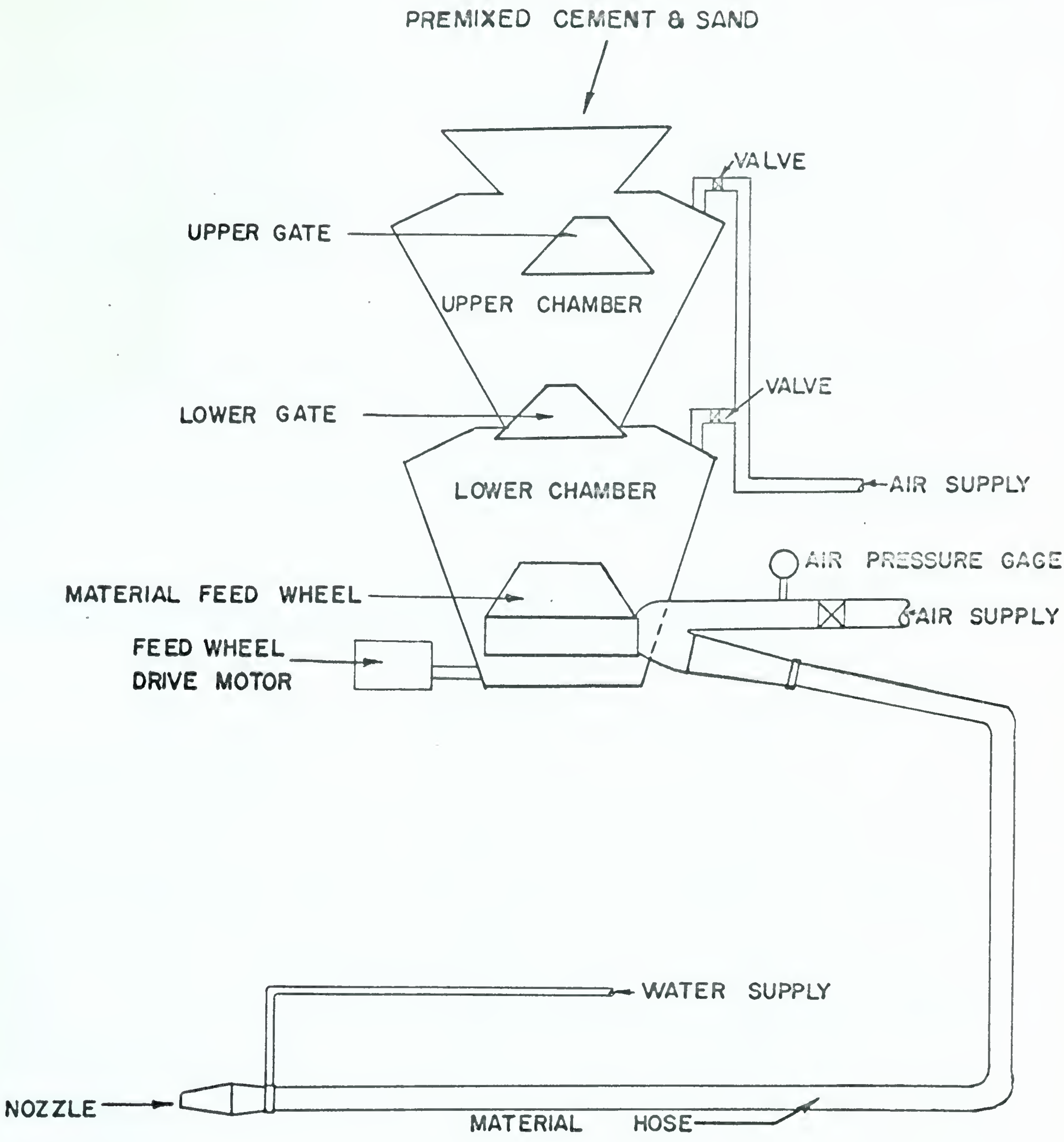


FIGURE NO. 4 ILLUSTRATION SHOWING OPERATING PRINCIPLE OF GUNITE MACHINE

to the material hose where it is carried along in the air stream. Water is added to the mix by means of a separate hose attached to the nozzle where a radial spray wets the mix as it flows by.

Equipment components used in this testing program included two 125 cfm rotary air compressors, 125 ft of 1-1/4 in. inside diameter material hose and a 3/4 in. nozzle.

GENERAL PROCEDURE FOR PLACING SHOTCRETE MATERIAL

The operation of shooting or placing shotcrete material is similar for both the Gun-All and Gunite processes. For the best results, the spray from the nozzle should hit the work as nearly as possible at right angles with the nozzle held from 1-1/2 ft to 3 ft from the work. The nozzle should be moved with a continuous to-and-fro or circular motion to insure uniform placement of material.

The material which bounces back from the working surface, referred to as "rebound", consists mostly of aggregate, especially the larger particles of aggregate. Care must be taken to prevent rebound from being trapped in the work since it may cause localized weak areas.

The consistency of shotcrete is critical because if it is too dry there will be excessive rebound, and if too wet it will slump down a vertical surface. Wall thicknesses up to 6 inches may be built up in one pass and successive layers may be added after the material has attained its initial set.

The high velocity of the jet from the nozzle results in compaction of the material in place. After placing it should not be vibrated or otherwise disturbed, but may be cut or scraped with a steel trowel or given a wood float finish to leave a satisfactory surface.

FIGURES 5 and 6 show shooting operations on a construction job, FIGURE 7 shows the appearance of a wood float finish, and FIGURE 8 shows compressive strength cylinders being fabricated on a construction job site.

FIGURE 5

Shooting a swimming pool floor

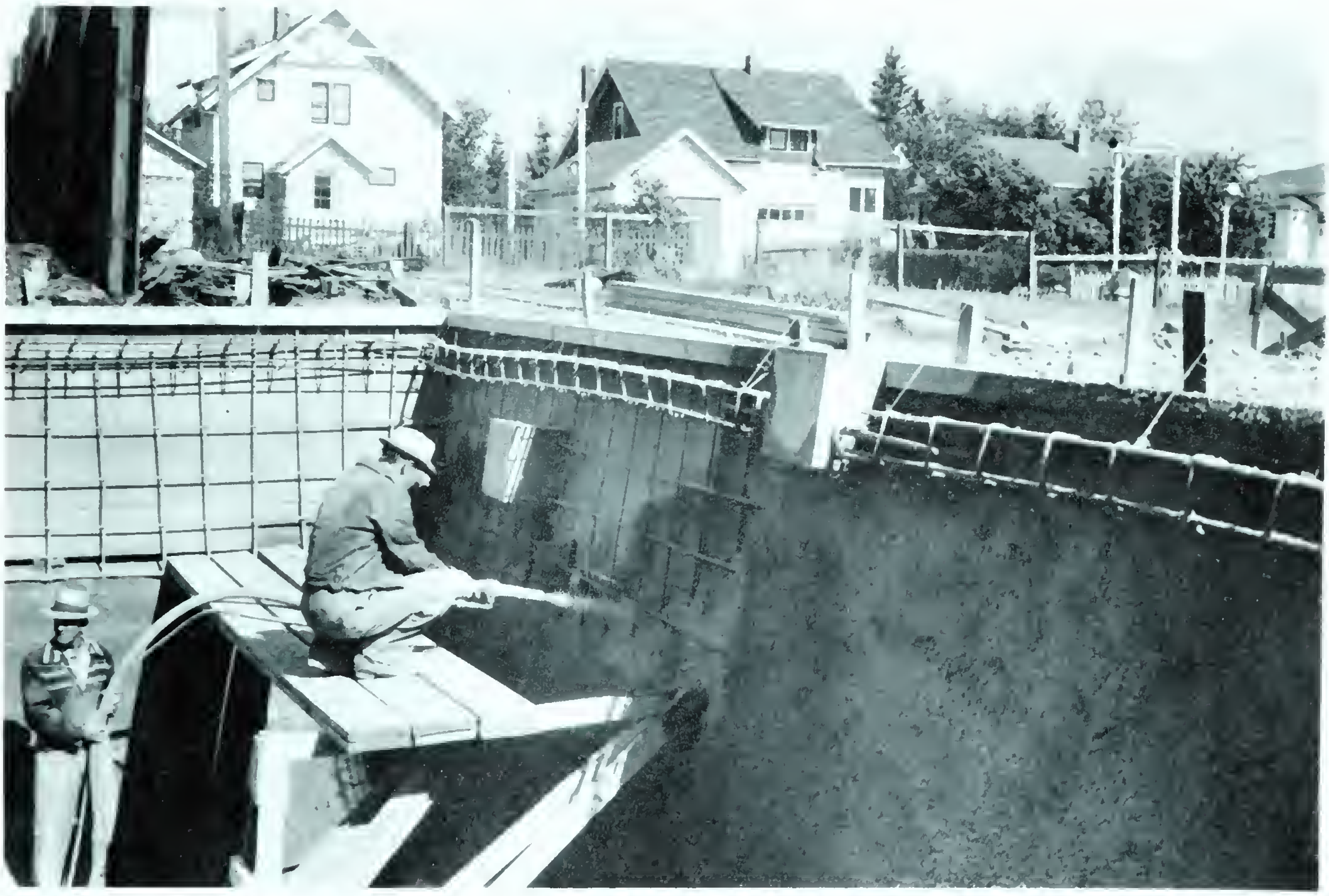


FIGURE 6

Shooting a wall

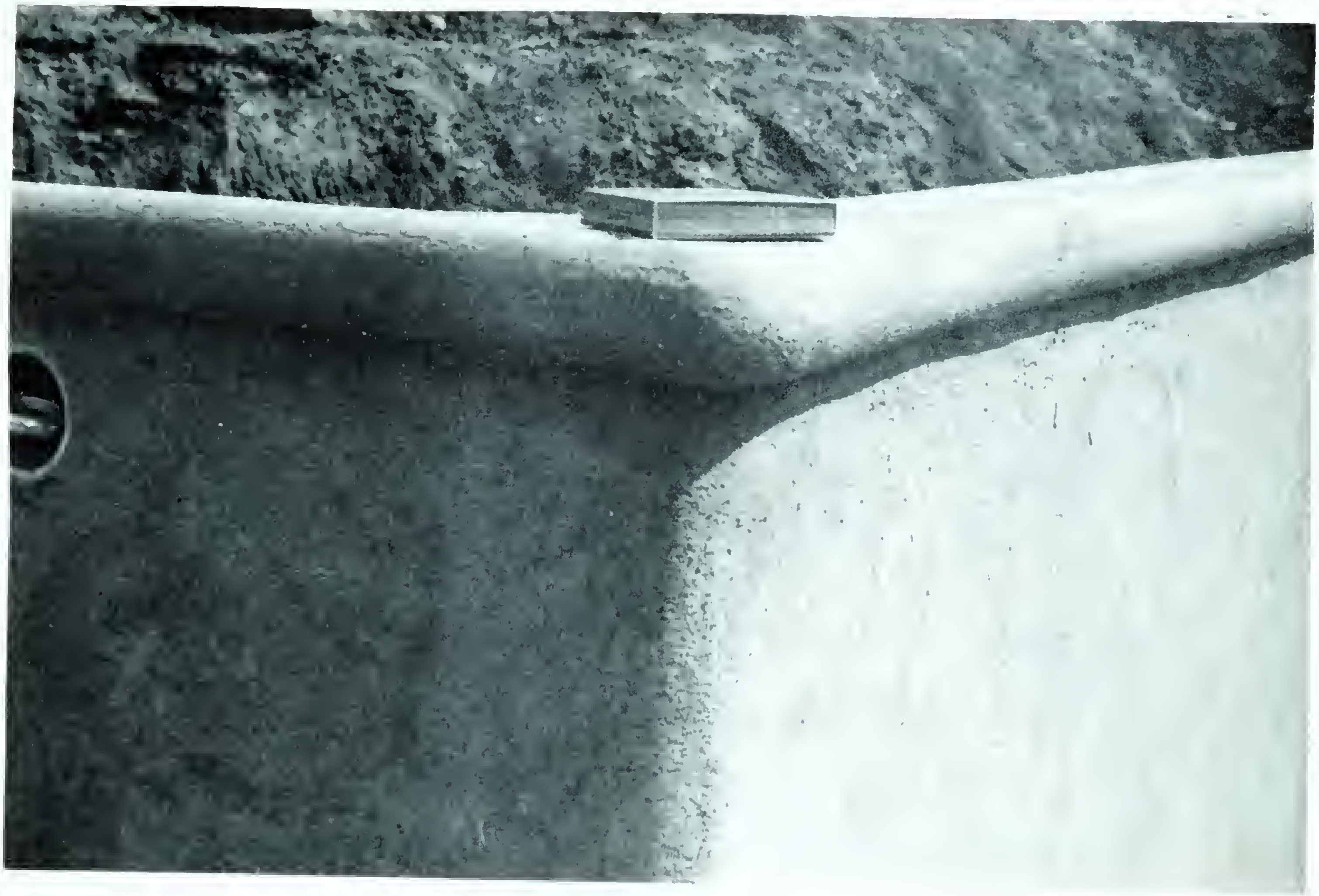


FIGURE 7

Wood float finish

FIGURE 8

Shooting cylinders of a wet mix at a construction job-site

CHAPTER III

OUTLINE OF TESTING PROGRAM

PROGRAM OUTLINE

TALBE 1 shows the batch proportions for the different mixes used. A D-2 Gun-All machine was used for the first twelve mixes which fall into three series, and an N-1 Gunite machine was used for Mix No. 13. In Series I the water-cement ratio was varied, in Series II the aggregate-cement ratio was varied and in Series III the aggregate gradation was varied.

In Series I of this testing program, the water-cement ratio was varied with progressively increasing water contents from Mix Nos. 1 to 5. Mix No. 3 was designed to be of a consistency which is normal for regular shotcrete work while Mix Nos. 1 and 2 were on the dry side and Mix Nos. 4 and 5 were on the wet side.

The remaining Gun-All mixes (Nos. 6 to 12 inclusive) were all designed to be of a consistency comparable to that of Mix No. 3. For these mixes, the aggregate-cement ratio was varied (Series II), and the aggregate gradation was varied (Series III). In order to maintain uniform consistency it was also necessary to adjust the water content

TABLE 1

PROGRAM LAYOUT - MIXES USED

SERIES NO.	DESCRIPTION OF SERIES	MIX NO.	BATCH PROPORTIONS BY WEIGHT - LBS. CEMENT	WATER TOTAL	SAND (DRY)	ROCK (3/8" CRUSH)
1.	AGGREGATE GRADATION	1	87.5	31	387	0
	HELD CONSTANT	2	87.5	40	387	0
	AGGREGATE-CEMENT RATIO	3	87.5	49	387	0
	HELD CONSTANT	4	87.5	57	387	0
	WATER-CEMENT RATIO	5	87.5	66	387	0
	VARIED					
2.	AGGREGATE GRADATION	7	87.5	50	236	0
	HELD CONSTANT	6	87.5	46	290	0
	CONSISTENCY HELD	3	87.5	49	387	0
	CONSTANT	8	87.5	54	492	0
	AGGREGATE-CEMENT RATIO					
	VARIED					
3.	CONSISTENCY HELD	9	87.5	48	344	50
	CONSTANT	10	87.5	45	295	100
	AGGREGATE-CEMENT RATIO	11	87.5	41	246	150
	HELD CONSTANT	12	87.5	38	197	200
	ROCK-SAND RATIO VARIED					
4.	"GUNITE"	13	4:1 SAND-CEMENT RATIO BY VOLUME WATER ADDED AT NOZZLE			

which resulted in a variable water-cement ratio. The water contents used for these mixes was determined by visual examination and by the "feel" of the material in preliminary laboratory investigations. Experience showed that if a handful of this "normal" shotcrete was squeezed tightly in the hand and dropped from a height of 1[illegible] ins. into a pan of hand mixed material, it would crumble. This admittedly crude test was used along with visual appearances to determine the water contents to be used for Mix Nos. 6 to 12.

The consistency tests for normal concrete (A.S.T.M. Designation C 143-52, Slump of Portland Cement, and A.S.T.M. Designation C 124-39 Flow of Portland Cement by Use of the Flow Table) are not adaptable to shotcrete since it is zero slump material and in terms of water content usually less than zero slump. In field work the criterion for consistency is that there must be sufficient water to prevent excessive rebound, but not so much as to cause the material to slump down from a vertical [illegible] surface. [illegible] 5 gives an indication of the consistency of a typical shotcrete mix in that there was only a slight indentation of the foot prints in the freshly placed material.

TESTS CONDUCTED

TABLE II outlines the number of test specimens which were made, and the tests which were conducted. Altogether, approximately 200 test specimens were made and tested to failure, 12 linear change specimens were made and 55 densities were determined.

MATERIAL USED

The cement for this testing program was supplied by an Edmonton cement manufacturer, the properties of which are shown in TABLE III. All of the cement used in this testing program came from the same shipment which was freshly manufactured, and delivered directly from the plant.

The aggregates used consisted of natural sand and crushed river gravel, and are more or less typical of the aggregates found in the Edmonton area. TABLE IV shows the properties of the aggregates and FIGURE [illegible] the gradation of the various aggregate mixes used. A total of 8,640 pounds of aggregates were weighed, bagged, and shot to make the test samples.

TABLE II

PROGRAM LAYOUT - TESTS CONDUCTED

SERIES NO.	MIX NO.	6 in. by 12 in. CYLINDERS COMPRESSIVE STRENGTH	STEEL BOND (PULL-OUT) SPECIMENS	CONCRETE TO CONCRETE BOND SPECIMENS	COMPRESSIVE STRENGTH 4 in. CUBES FROM CONCRETE BOND SPECIMENS	FLEXURAL STRENGTH 4 in. by 4 in. BEAMS	COMPRESSIVE STRENGTH 4 in. CUBES FROM FLEXURAL STRENGTH SPECIMENS	LINEAR CHANGE SPECIMENS (2 SETS OF PINS EACH)
1	1	2	3	3		3		1
	2	2	3	3		3		1
	3	2	3	3		3		1
	4	2	3	3		4		1
	5	2	3	3		2		1
2	6	2	3	3		2		1
	7	3	3	3	3	4	3	1
	8	3	3	3	3	4	3	1
3	9	3	3	3	3	4	3	1
	10	3	3	3	3	4	3	1
	11	3	3	3	3	4	3	1
	12	3	3	3	3	3	3	1
4 (GUNITE)	13	3	3	3	3	2	3	

- THE DENSITIES OF ALL 6 in. by 12 in. CYLINDERS AND 4 in. CUBES FROM THE FLEXURAL SPECIMENS WERE DETERMINED

- MIX NO. 10 - 35 - 4 in. CUBES FOR COMPRESSIVE STRENGTHS AT VARIOUS AGES

TABLE III

PROPERTIES OF TYPE I PORTLAND CEMENT *

Physical Properties

Setting Times: Initial, 2 hr. 30 min, Final, 4 hr. 20 min.

Fineness, No. 200 Sieve, 97.4% (passing)

Autoclave Expansion, 0.22%

Compressive Strength, psi 2710, 3530, 5300.

Strength tests at 3, 7, and 28 days.

325 Sieve - 94.4% passing; Fineness - Blaine (CM^2-gm) 3210

Normal Consistency - 24.5%

Chemical Tests

Silica (SiO_2)	21.69%	LR = 2.23
Alumina (Al_2O_3)	4.61%	SR = 3.14
Iron Oxide (Fe_2O_3)	2.2[illegible]%	AR = 2.03
Calcium Oxide (CaO), Total	63.77%	C_4AF = 6.9
Calcium Oxide (CaO), Free	1.26%	C_3A = 8.3
Magnesium Oxide (MgO)	3.78%	C_3S = 51.5
Sulphur Trioxide (SO_3)	1.70%	C_2S = 22.7
Loss on Ignition	1.66%	$CaSO_4$ = 2.9
Insoluble Residue	0.13%	

* - Results of Analysis Conducted by Canada Cement Company Limited, Edmonton

TABLE IV

PROPERTIES OF AGGREGATES USED

PROPERTY		SAND	GRAVEL
Gradation			
% Retained	3/8 in.	0	0
	No. 4	0	71.6
	No. 8	3.6	25.9
	No. 16	2.0	0.9
	No. 30	36.6	0.0
	No. 50	45.2	.5
	No. 100	5.5	.4
Fineness Modulus		2.29	5.64
Coal Content		Nil	Nil
Shape		Rounded	Angular
Percent Crush			95
Organic Color No.		3	

TABLE V

PROPERTIES OF REINFORCING STEEL USED

	No. 4 Bars	No. 6 Bars
Nominal Diameter	½ in.	3/4 in.
Yield Point	50,000 psi	50,000 psi
Deformations		
Spacing	0.32 in.	0.52 in.
Width	0.10 in.	0.10 in.
Heigth	0.04 in.	0.06 in.

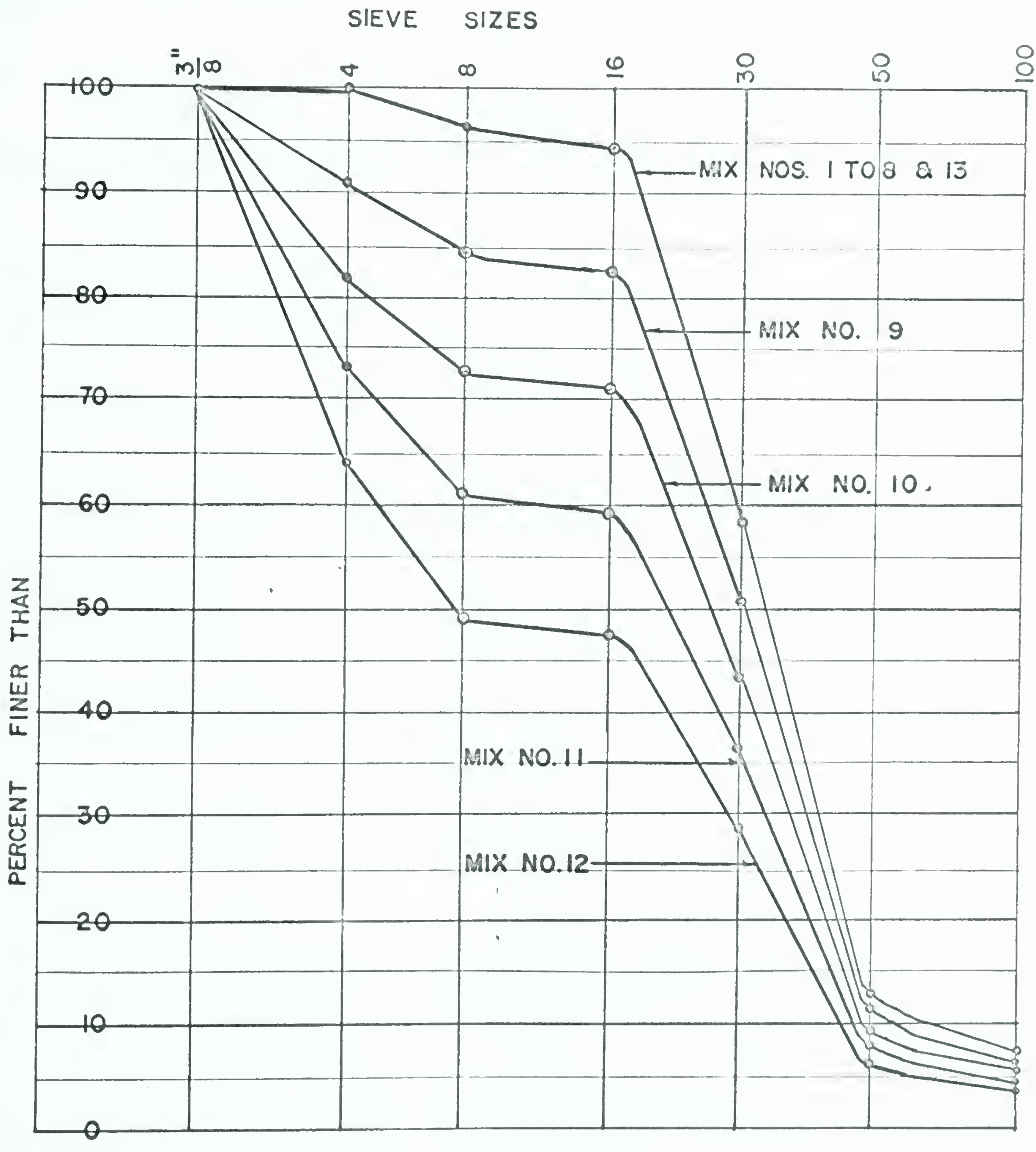


FIGURE NO. 9 GRADATION OF VARIOUS AGGREGATE MIXES USED

The mixing water used was taken from the City of Edmonton water mains.

TABLE V shows the properties of the reinforcing steel bars which were used.

CHAPTER IV

FABRICATION OF TEST SPECIMENS

GENERAL CONSIDERATIONS

From a literature search it was evident that there was little precedence to go on for the fabrication of the shotcrete test specimens. The standard methods used for normal concrete involving enclosed forms are not adaptable to shotcrete since the air blast and rebound must freely escape from the work. To meet this requirement, open mesh molds and one sided forms were used for the fabrication of all of the specimens in this program.

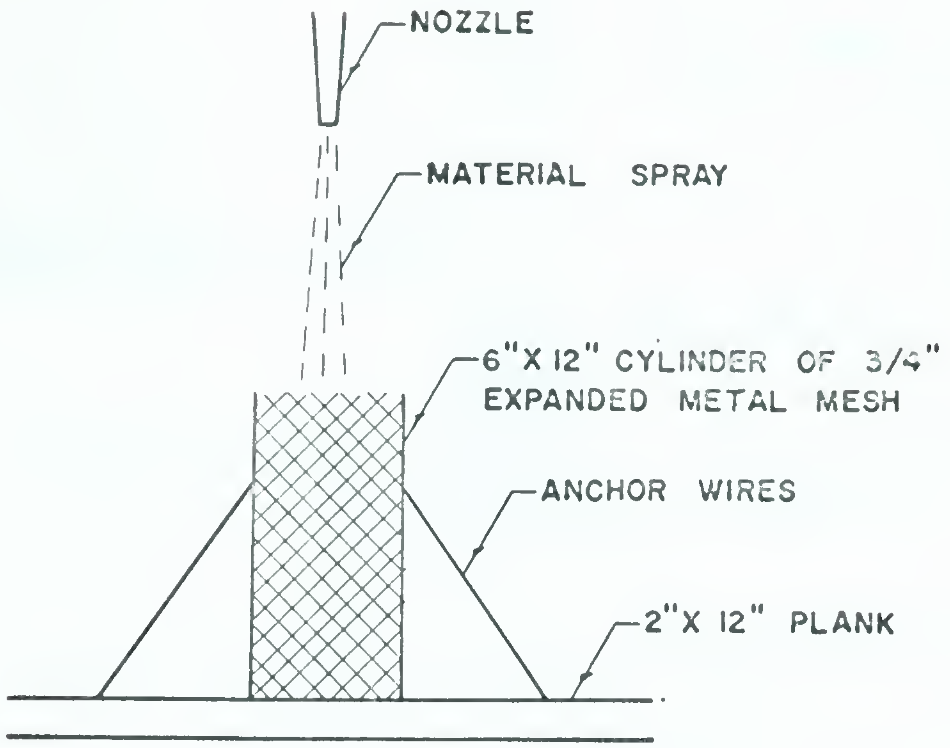
MOLDS AND FORMS USED FOR FABRICATING TEST SPECIMENS

The A.C.I. (1) outlines a procedure for making 6 in. by 12 in. cylinders, which is quoted as follows: "Test cylinders should be made by shooting shotcrete into a mold of hardware cloth (3/4 in. metal mesh) to make cylinders 6 in. in diameter and 12 in. long. The excess

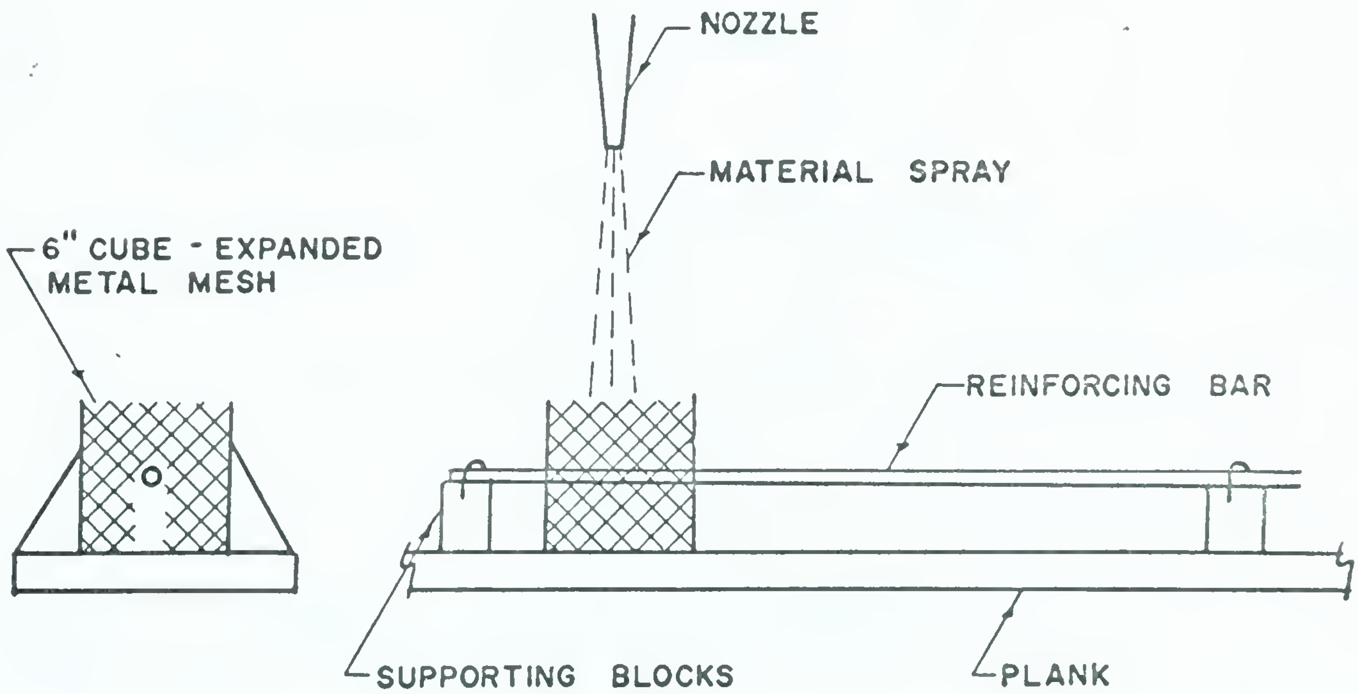
material outside the mold is trimmed off with a sharp edged trowel. The open mesh mold is used to permit the escape of air and rebound during placement and provides a cylindrical guide to trim to. About 24 hours after making the cylinders, the hardware cloth form should be removed and the cylinders stored under moist curing conditions at approximately 70° F until tested under A.S.T.M. Designation C 39-42." This method was used for the cylinders in this testing program, as shown in FIGURE 10.

The procedure used for the 6 in. by 12 in. cylinders served as a guide for fabricating the steel bond specimens and the concrete to concrete bond specimens, as shown in FIGURES 10 and 11.

For the steel bond tests, an adaptation of the standard test as outlined by A.S.T.M. Designation C 234-54 was used. In this A.S.T.M. test, reinforcing bars with a nominal diameter of 3/4 in. are cast in 9 in. cubes of concrete. For Mix Nos. 1 to 6, 1/2 in. diameter bars were used in 6 in. cubes of shotcrete. These two combinations have an equivalent ratio of the surface area of the embedded steel divided by the cross-sectional area of the steel bar. Six in. cubes were used rather than the standard 9 in. cubes because shotcrete is generally applied



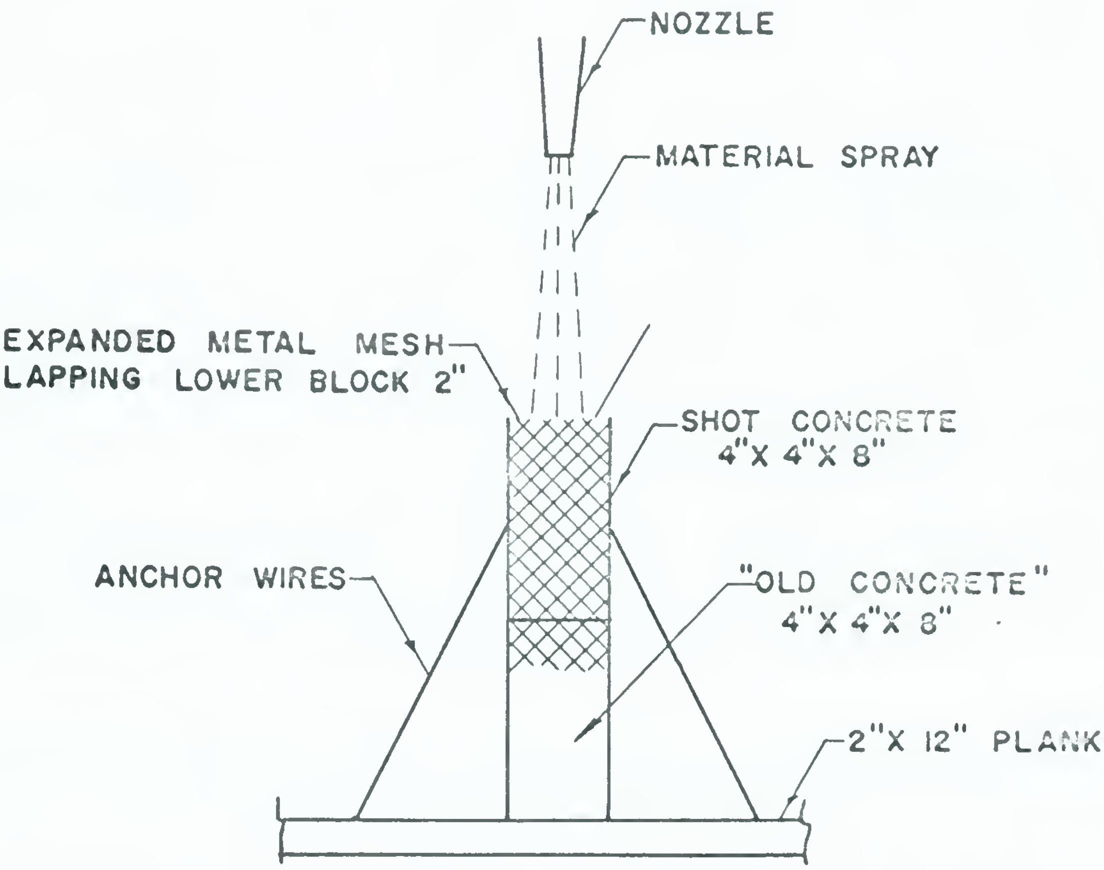
MOLD FOR 6" × 12" CYLINDER



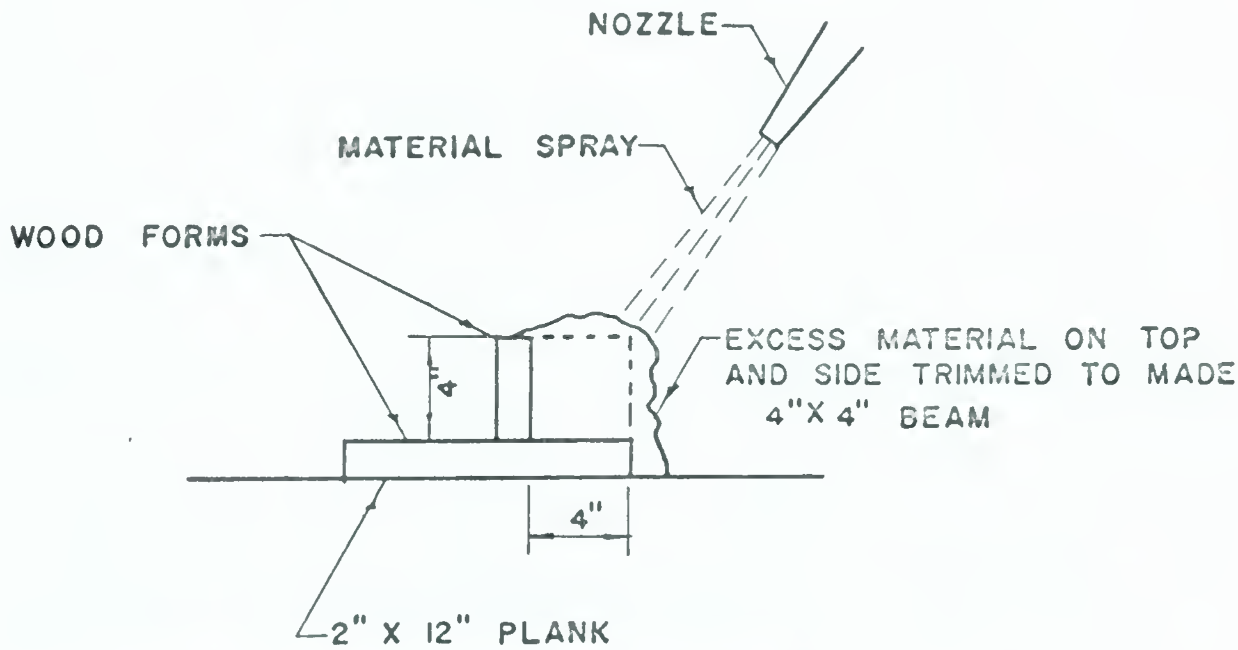
END VIEW   SIDE VIEW

MOLD FOR STEEL BOND SPECIMEN

FIGURE NO. 10 MOLDS FOR 6" X 12" CYLINDERS AND STEEL BOND SPECIMENS



MOLD FOR CONCRETE TO CONCRETE BOND SPECIMEN (COMPOSITE BEAM)



FORM FOR 4" X 4" BEAM

FIGURE NO.11 MOLDS FOR COMPOSITE AND MONOLITHIC BEAMS

in relatively thin sections, and this smaller size was considered to be more representative of shotcrete. When the steel bond specimens for Mix Nos. 1 to 6 were tested, it was found in the majority of cases that the No. 4 reinforcing bars yielded and therefore, in Mix Nos. 7 to 12, No. 6 bars were used instead of No. 4 bars.

As shown in FIGURE 10, the steel bond test specimens were made with an expanded metal mesh cage, 6 in. by 6 in. by 6 in. The reinforcing bar, which passed through the centre of the cube, was supported on wooden blocks and fastened for rigidity.

The concrete to concrete bond specimens consisted of composite 4 in. by 4 in. by 16 in. beams, as shown in FIGURE 11. The "old concrete" portions of the beams (8 in. long) were made the same way as the flexural strength beams, described below, one month before the first series of specimens were shot. A rich mix was used in the "old concrete" to ensure that failure would occur in the "shot concrete" portion of the beams. The ends were trimmed by scraping with a trowel edge, leaving a rough textured surface. The specimens were cured under moist burlap until the time the other half of each beam was shot. Approximately 10 minutes before shooting, the "old concrete" pieces were

moistened to minimize the absorption of water from the new concrete.

The 4 in. by 4 in. flexural beams were made using wooden forms on the bottom and one side as shown in FIGURE 11. The forms were soaked with water for one day before shooting the specimens. After shooting, the excess material was trimmed from the top and one remaining side.

Using Mix No. 10, thirty-five 4 in. cubes were made for compressive strength testing at various ages. A 4 in. by 4 in. beam approximately 20 ft long was shot using forms similar to that previously described for flexural beams. Using one chamber of mix, the beam was shot progressively from one end to the other. After shooting, the excess material was trimmed and the beam was cut into eight 2-1/2 ft lengths, which were numbered from 1 to 8. These beams were sawn into 4 in. lengths to make the 4 in. cubes which were then cured and tested for compressive strength at various ages.

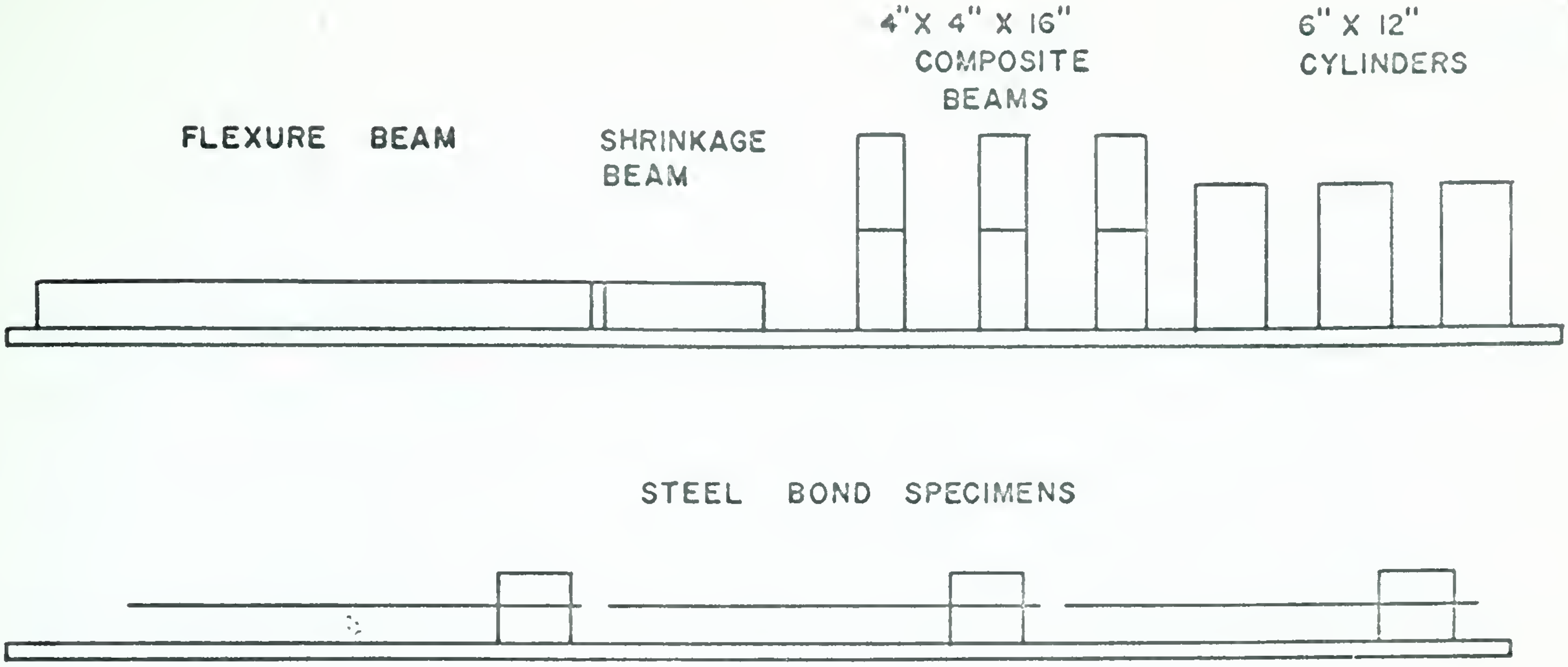
The linear change test specimens, beams 4 in. by 4 in. by 1[illegible] in., were shot and trimmed in the same manner as the flexural beams. After the concrete had reached its

initial set, two sets of gage points were attached to the top of the beams without disturbing them in their original position.

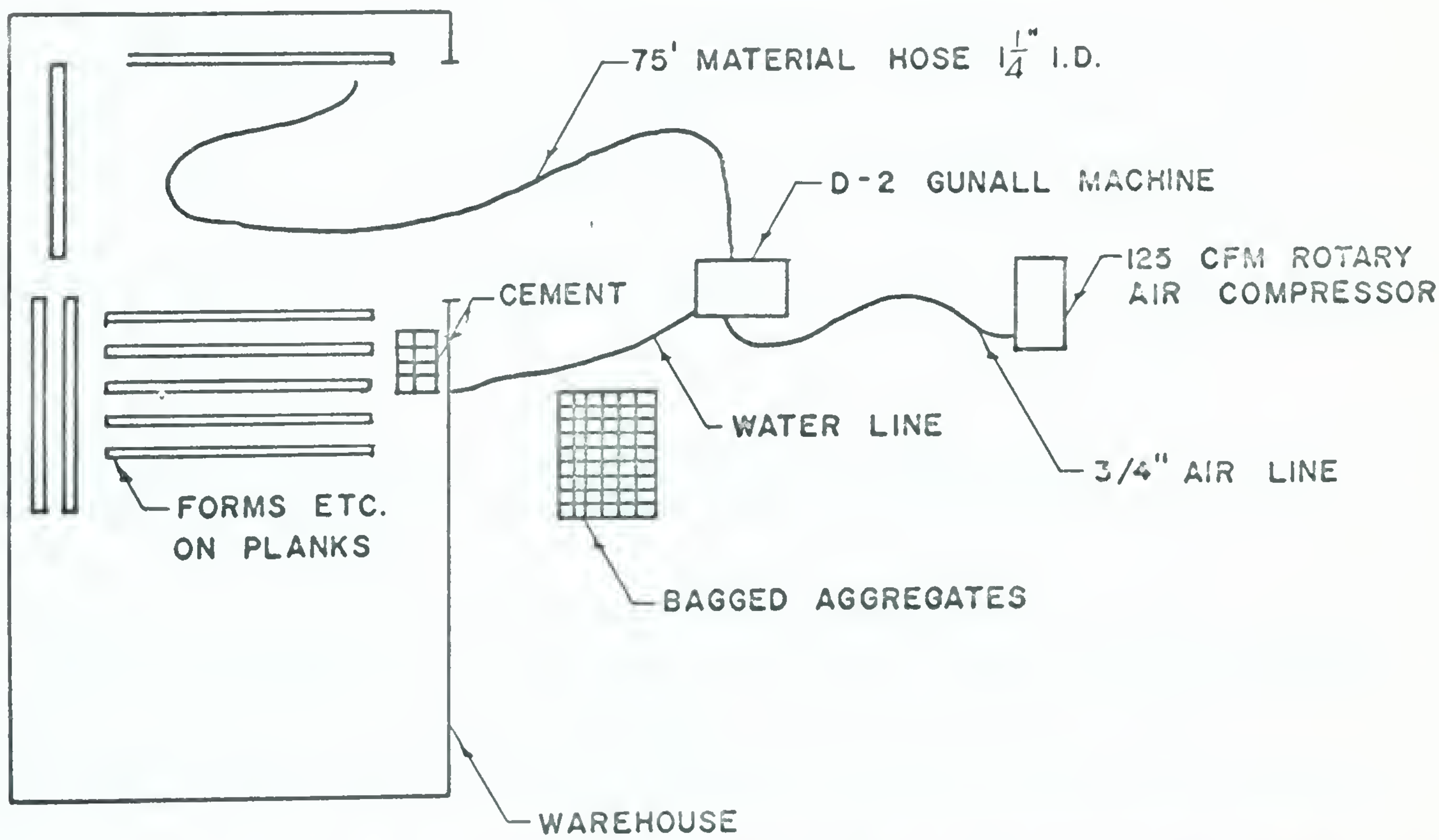
FABRICATION OF TEST SPECIMENS

All of the test specimens were made at the warehouse of the Edmonton firm which supplied the shooting equipment, operators, and other facilities required. Six cu yds of sand and one cu yd of 3/8 in. crush aggregate were stock-piled in the yard near the warehouse. The aggregates for each of the Gun-All mixes were weighed in bags, tagged and covered with polythene until they were used. In the morning before shooting the samples, the moisture content of the bagged aggregates was checked, and the quantities of additional mixing water adjusted accordingly. Molds and forms were made up for six mixes, and set up as shown in FIGURE 12. The water meter on the Gun-All machine was calibrated to ensure accurate determination of mixing water quantities.

The crew which shot all of the test specimens consisted of a nozzleman who had had ten years experience with shotcrete, an experienced equipment operator, and one man loading the machine.



FORM SETUP FOR ONE MIX



PLAN VIEW OF OVER-ALL SETUP FOR SHOOTING SAMPLES

FIGURE NO.12 SETUP FOR SHOOTING TEST SPECIMENS

Just prior to shooting the specimens, one chamber full of material was mixed, shot and wasted, to wet the inside of the mixing chamber and material hose, and also to provide an opportunity to adjust the air regulators. Two or three chambers full of material were required for each mix, but to eliminate one possible variable, only one of the two mixing chambers was used.

On July 11, 1961, Mix Nos. 1, 2, 3 and 4 were shot, and on July 12, Mix Nos. 5 and 6 were shot. Because of the amount of specimen preparation and testing required, the remaining six Gun-All mixes were not shot until after the 28 day tests were conducted on the first six mixes. Mix Nos. 7 to 12 were shot on August 14, 1961 using the same procedures as for the first six mixes.

VISUAL OBSERVATIONS MADE AT THE TIME OF SHOOTING

The following is a summary of the visual observations made at the time each mix was shot.

Mix No. 1 was excessively dry with very excessive rebound. It was estimated there would be at least 50% rebound if this material were shot on a wall. The material

flowed unevenly from the nozzle with a variable velocity. It seemed that there was some trapped rebound in the specimens. In summary, the mix was too dry for a good operation. Three chambers full of mix were necessary to shoot all of the specimens (2 chambers full were sufficient for each of the remaining mixes).

Mix No. 2 produced considerable rebound, which was estimated to be 30% to 40% if this mix were shot on a wall. The mix was still too dry for good operation.

Mix No. 3 appeared to be near what might be called an "average" consistency for shotcrete. The material came out of the nozzle fairly uniformly and it was estimated there would be about 10% rebound if this mix were shot on a wall. The material could be steel trowelled with some difficulty.

Mix No. 4 appeared to be slightly too wet for shooting on walls but approximately of the consistency that would be used in shooting a floor. The material flowed from the nozzle quite evenly.

Mix No. 5 appeared to be too wet for normal Gun-All operation. The flow from the nozzle was quite uniform and a fog of water was also apparent coming from the nozzle along with the mix material.

Mix No. 6 appeared to be of a consistency similar to that of Mix No. 3 and the material flowed evenly from the nozzle.

Mix No. 7 inadvertently was batched with more mixing water than was planned, thus for the second chamber full, an equivalent amount of water was used. It was impossible to re-shoot Mix No. 7 because the time was not available. The material from Mix No. 7 appeared to be slightly wetter than Mix No. 3 and the material flowed evenly from the nozzle.

Mix No. 8 appeared to be of a consistency similar to that of Mix No. 3, however, the material flowed a little less evenly through the nozzle.

Mix Nos. 9 to 12 each appeared to be of a consistency similar to that of Mix No. 3. The flow from the nozzle was good but slightly intermittent. Mix Nos. 9 to 12 contained progressively more 3/8 in. crush aggregate, and increasing amounts

of this coarser aggregate caused greater percentages of rebound, estimated to be from 10% to 30%.

FABRICATION OF GUNITE SPECIMENS (MIX NO. 13)

The molds and forms used to obtain the Gunite test specimens were the same as those used for the Gun-All specimens as previously described. The sand and cement were volume batched at a 4:1 ratio and sufficient mixing water was added at the nozzle to produce a consistency similar to that of Mix No. 3, as nearly as the nozzle operator could judge.

The Gunite specimens were shot on August 16, 1961, and were cured and tested in the same manner as the Gun-All specimens.

TRIMMING AND CURING THE TEST SPECIMENS

Between 1/2 hour and 2 hours after the test specimens were shot the excess material was trimmed from the outside of the expanded metal mesh forms, and the beams were trimmed to the proper dimensions. The specimens were cured under moist burlap in their original position for the first 24 hours.

FIGURES 13 and 14 show the test samples for Mix Nos. 7 to 12 in their original position.

When the specimens were 24 hours old, the expanded metal mesh forms were removed and the specimens were moved from warehouse to the concrete moist room at the Civil Engineering Building, University of Alberta, where they were cured under moist conditions until the time of testing. FIGURE 15 shows the concrete to concrete bond specimens and the 6 in. by 12 in. cylinders for Mix Nos. 1 to 7. FIGURE 16 also shows the flexural beams, the linear change beams, and the steel bond specimens. The photos were taken just before the samples were moved to the Civil Engineering Building.

FIGURE 13

Test specimens for mix Nos. 7 to 12, just after they were shot, trimmed and covered with wet burlap

FIGURE 14

Steel bond specimens with excess material trimmed

FIGURE [illegible]

Composite beams and 6 in. by 12 in. cylinders

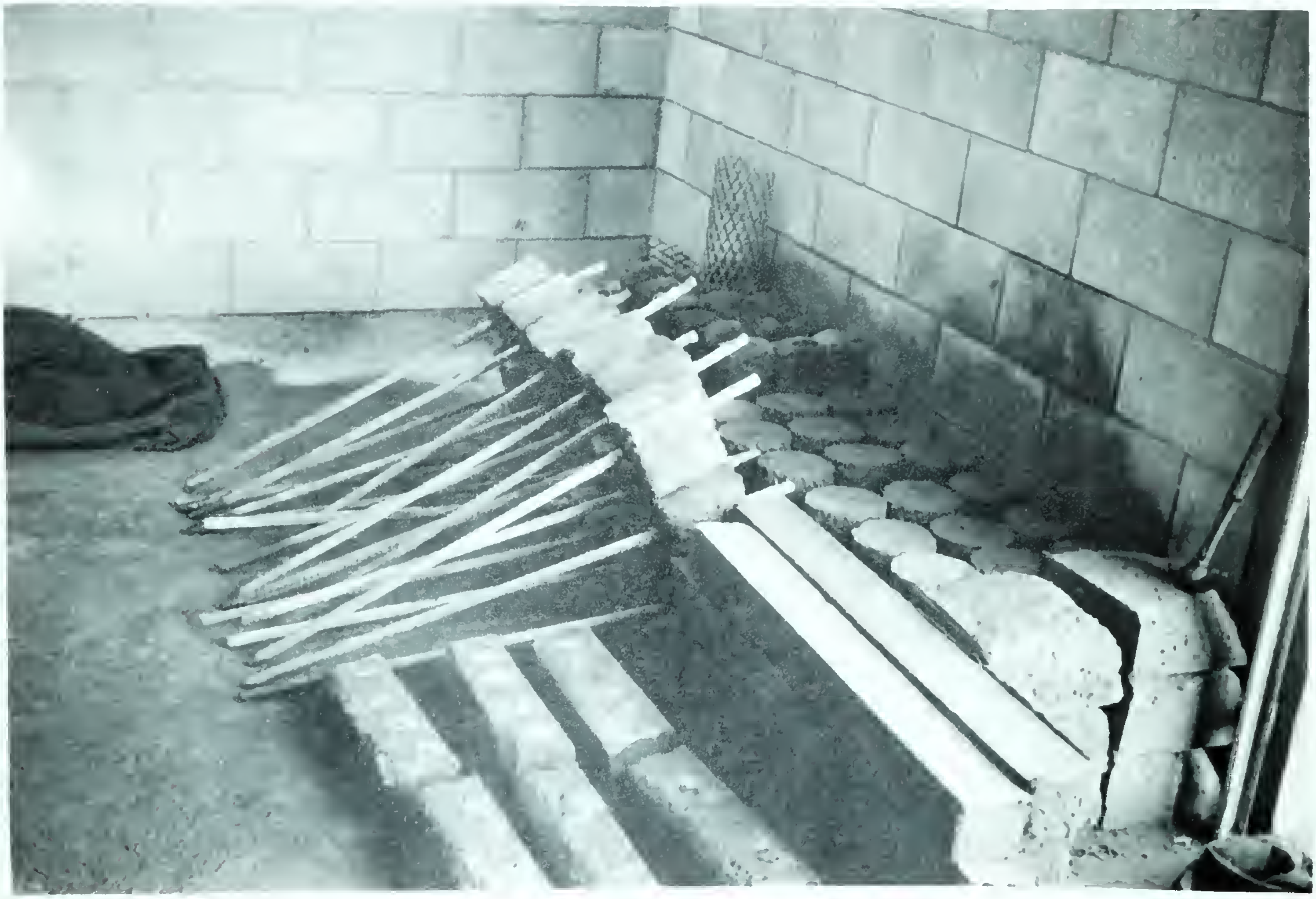


FIGURE [illegible]

Back row - composite beams and 6 in. by 12 in. cylinders
Front row - [illegible], [illegible] beams,
[illegible]

CHAPTER V

METHODS OF CONDUCTING TESTS

DENSITY TESTS

The densities of all of the 6 in. by 12 in. cylinders and the 4 in. cubes from the flexural beams for Mix Nos. 7 to 13 were determined. The densities of these specimens were obtained by weighing them in air, weighing them submerged in water, and then re-weighing in air with corrections for absorption where necessary. A sample calculation is shown in Appendix A.

COMPRESSIVE STRENGTHS OF 6 in. by 12 in. CYLINDERS

The compressive strengths of the 6 in. by 12 in. cylinders were determined in accordance with A.S.T.M. Designation: C 39-49. They were capped with sulphur and tested in a hydraulic testing machine which applied the load at a constant rate of 50 psi per sec.

FLEXURAL STRENGTH TESTS

Flexural-strength tests were conducted in accordance with A.S.T.M. Designation: C 78-49 for third point loading on 4 in. by 4 in. beams over a 12 in. span length. Sample calculations for the determination of the modulus of rupture are shown in Appendix A.

CONCRETE TO CONCRETE BOND TESTS

The concrete to concrete bond tests were conducted on composite beams which were broken in flexure in the same manner as the monolithic flexural beams. Where the concrete surfaces were rough at the point of contact with the loading blocks, they were capped with sulphur. The joint between the old concrete and the new was placed at mid-span. The modulus of rupture was determined as in the flexural-strength tests.

COMPRESSIVE STRENGTH OF 4 in. CUBES

Four inch cubes were cut from the various beams and tested in compression, the sawn faces were capped with sulphur and used as the bearing surfaces. They were tested in a hydraulic testing machine at a rate of loading of 50 psi per sec.

REINFORCING STEEL BOND TESTS

The steel bond tests consisted of pull-out tests of reinforcing bars embedded in 6 in. cubes of shotcrete. The shotcrete surfaces which were to come into contact with the bearing block of the testing machine were capped with sulphur to provide smooth flat surfaces perpendicular to the protruding reinforcing bars. The specimens were mounted in a hydraulic testing machine in such a way that the long ends of the reinforcing bars extended downwards through the one inch diameter hole bearing block of the testing machine. The bottom ends of the reinforcing bars were gripped for tension by the jaws of the testing machine. The load was applied at the rate of 5,000 lbs per min. Slip at the free end of the reinforcing bars was measured by means of a 0.001 inch dial gage, attached directly to the free end of the reinforcing steel with the stem of the gage in contact with the top of the shotcrete.

LINEAR CHANGE MEASUREMENTS

The linear change test specimens consisted of 4 in. by 4 in. by 16 in. beams with two sets of gage points attached to the top surface of the beams. Readings were taken with a "Demec" gage which is a linear mechanical extensometer.

Initial readings were taken as soon as possible after the installation of the gage points, usually from 1-1/2 to 5 hours after the concrete was shot. Subsequent readings were taken several hours later to check for any loose gage points and also for any movements due to the concrete having had insufficient time to attain final set.

At the time of the initial reading, the concrete temperature was determined by embedding a thermometer in the material which was trimmed from the beams. The temperatures taken with all subsequent Demec Gage readings were obtained by embedding a thermometer in some aggregate which was stored near the specimens.

CHAPTER VI

TEST RESULTS AND ANALYSIS

INCREASE OF COMPRESSIVE STRENGTH WITH TIME

TABLE VI shows the compressive strengths of the 4 in. cubes which were broken at various ages. In addition to the strength-time relationship for these cubes, an attempt was made to determine any variation in the strength of the material from the beginning of one batch to the end of it. The 20 ft long beam from which the cubes were obtained was shot progressively from one end to the other, from one batch of material. When this was cut into 2-1/2 ft lengths, the pieces were numbered from 1 to 8. The three cubes broken on any particular day were taken from various places along the beam. The results show that there were no particular differences in strengths of the cubes from one end of the beam to the other. This indicates that the material was probably fairly uniform from the beginning to the end of one batch.

TABLE VI

COMPRESSIVE STRENGTHS VERSUS TIME
4 in. CUBES - MIX NO. 10

DATE SHOT - AUGUST 14, 1961

DATE BROKEN	AGE (days)	PORTION OF BEAM	TOTAL LOAD (lbs)	COMPRESSIVE STRENGTH (psi)	AVERAGE COMPRESSIVE STRENGTH (psi)
1961					
Aug. 15	1.0	8	34,200	2140	
		7	36,200	2260	
		1	31,000	1940	2110
16	2.3	7	65,000	4060	
		1	65,600	4100	
		7	62,400	3900	4020
17	3	7	65,000	4090	
		1	65,600	4930	
		7	76,300	4760	4600
18	4	3	81,100	5060	
		4	85,100	5320	
		6	77,500	4850	5080
21	7	2	87,200	5450	
		3	90,000	5630	
		5	80,000	5000	5360
24	10	2	86,600	5410	
		4	75,000	4690*	
		6	93,000	5810	5610
Aug. 31	17	3	104,300	6510	
		5	103,000	6440	
		7	98,200	6140	6360
Sept. 11	28	3	106,500	6660	
		4	97,000	6060	
		5	103,600	6480	
		6	108,800	6800	
		7	97,500	6090	6420
July 8/63	694	1	140,000	8750	
		2	141,000	7560	
		3	117,000	7320	
		4	130,000	8130	
		5	134,000	8370	
		6	129,000	8060	
		6	140,000	8750	
		[illegible]	137,000	8560	
		8	131,000	8180	8190

FIGURE 17 shows the plot of compressive strength versus age for 4 in. cubes from Mix No. 10. Each point on the graph up to the age of 17 days, is the average strength of three cubes, the 28 day point is the average of five cubes, and the 694 day point is the average of nine cubes. Expressed in terms of the 28 day strength, the 24 hour strength was 33%, the 7 day strength was 84% and the 694 day strength was 128%.

STATISTICAL ANALYSIS OF COMPRESSIVE STRENGTHS OF 4 in. CUBES

The compressive-strength results of the nine 694 day cubes were analysed using A.C.I. methods (9), the calculations and results of which are shown in TABLE VII. The coefficient of variation using the factor (n) was 5.7%, however, since the number of samples was small (only 9) the coefficient of variation was also calculated using the factor (n - 1) in place of (n). Using this method, the coefficient of variation becomes 6.0%. This analysis of nine cube strengths from one batch mix of shotcrete, of course, is not adequate to establish generally the within-test variation for shotcrete, however, it does show the trend for this particular group of nine cubes.

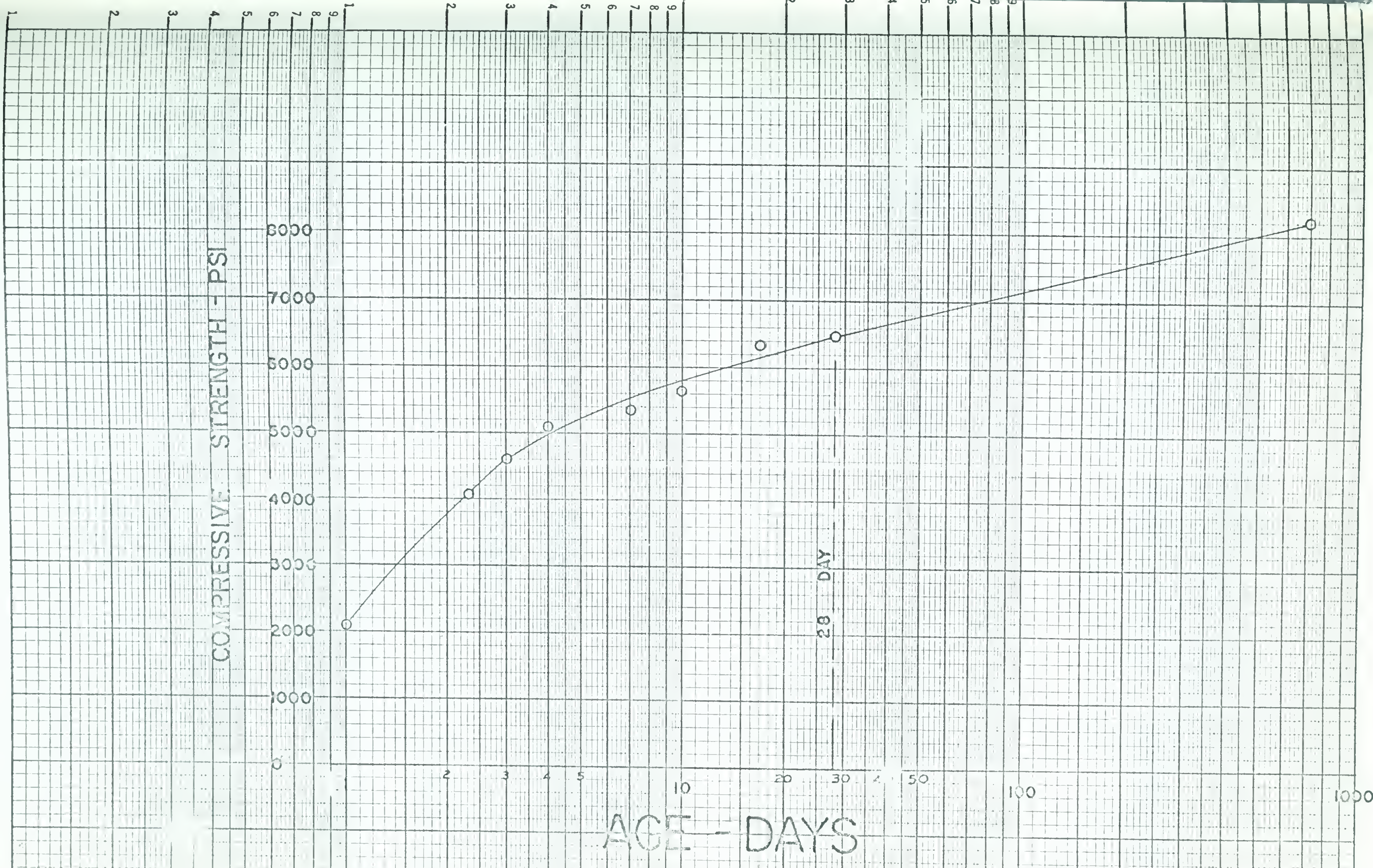


FIGURE NO. 17 INCREASE OF COMPRESSIVE STRENGTH WITH TIME
4 IN. CUBES - MIX NO. 10

TABLE VII

STATISTICAL ANALYSIS OF COMPRESSIVE STRENGTHS

OF 4 in. CUBES FROM STRENGTH VERSUS AGE GROUP (MIX NO. 10)

X	$X-\bar{X}$	$(X-\bar{X})^2$
8750	563	316,969
7560	627	393,129
7320	867	751,689
8140	47	2,209
8370	183	33,489
8060	127	16,129
8750	563	316,969
8550	363	131,769
8180	7	49

$\Sigma X = 73{,}680$

$\bar{X} = 8{,}187$

$1{,}962{,}401 = \Sigma(X-\bar{X})^2$

$218{,}045 = \dfrac{\Sigma(X-\bar{X})^2}{n}$

$\sigma = 467 = \sqrt{\dfrac{\Sigma(X-\bar{X})^2}{n}}$

$V_\sigma = \dfrac{\sigma}{\bar{X}} \times 100 = 5.7\%$

$s = \sqrt{\dfrac{\Sigma(X-\bar{X})^2}{n-1}}$

$s = 495$

$V_s = \dfrac{s}{\bar{X}} \times 100 = 6.0\%$

X = Compressive Strength of Various Cubes

n = No. of Cubes (9)

$\bar{X}$ = Average Compressive Strength $= \dfrac{\Sigma X}{n}$

σ = Standard Deviation (using n)

s = Standard Deviation (using n-1)

V = Coefficient of Varation

SUMMARY OF THE VARIOUS 28 DAY TEST RESULTS

The 28 day test results are summarized in TABLES VIII, IX and X, along with the averages for each type of test for each mix.

COMPARISONS OF COMPRESSIVE STRENGTHS AND DENSITIES OF 6 in. by 12 in. CYLINDERS

FIGURE 18 shows the compressive strength and density of the 6 in. by 12 in. cylinders plotted against the water-cement ratio for Series I, the aggregate-cement ratio for Series II, and the rock-total aggregate ratio for Series III.

In Series I, the aggregate gradation was held constant, the aggregate-cement ratio was held constant (387 lbs of sand per sack of cement) and the water-cement ratio was varied as shown in the graph. The results indicate that there is an optimum water content at which maximum compaction or density is attained, and also the maximum compressive strength is attained at this maximum density. Since the void ratio is related to the density, it appears that the void-cement ratio is a critical factor as well as the water-cement ratio. The increase in the water-cement ratio beyond the optimum caused a decrease in strength, in accordance with the general water-cement ratio law.

TABLE VIII

TEST RESULTS MIX NOS. 1 TO 6 (28 DAY)

6 in. by 12 in. CYLINDERS — MODULUS OF RUPTURE OF FLEXURAL BEAMS

Mix No.	Compressive Strength psi	Density lb per cu ft	Composite Beams psi	Monolithic Beams psi	Steel Bond Ultimate Stress psi
1	1080	122.9	60	450	430
	1260	122.0	340	470	630
			40	490	720
	1170	122.5	150	470	593 AVE
2	3040	138.4	420	750	980
	3930	139.6	300	570	1070
			350	620	1060
	3480	139.0	360	650	1037 AVE
3	5200	140.4	500	680	1470
	5610	141.7	480	640	1510
			550	700	1460
	5400	141.0	510	670	1480 AVE
				520	
4	3630 *	139.3	580	410	1280
	5030	139.7	440	580	1500
			600	390	1380
	5030	139.5	540	475	1387 AVE
5	4880	141.1	480	470	990
	4260	139.6	520	580	1060
			330		1200
	4570	140.3	440	525	1083 AVE
6	7440	141.9	500	360	1140
	7160	142.6	600	530	12[illegible]0
			680		1280
	7300	142.2	590	445	1233 AVE

NOTE * Faulty Sample - Rebound

TABLE IX

TEST RESULTS MIX NOS. 7 to 10 (28 DAY)

Mix No.	6 in. by 12 in. CYLINDERS Compressive Strength psi	Density lb per cu ft	COMPOSITE BEAMS Modulus of Rupture psi	Compressive Strength 4 in. Cubes psi	MONOLITHIC BEAMS Modulus of Rupture psi	Compressive Strength 4 in. Cubes psi	Density 4 in. Cubes psi	Steel Bond Ultimate Stress psi
					1020			
7	2850*	142.5	460	7250	980	6250	143.4	1110
	3540	142.9	620	7750	990	6650	142.5	950
	2470*	142.4	650	7600	900	6950	143.5	1010
	AVE 3540	142.6	580	7540	970	6620	143.1	1023
					675			
8	3300	140.6	410	4280	845	4800	140.2	800
	2750*	139.2	410	3850	770	6200	140.5	790
	3250	140.0	380	4780	660	5400	140.4	880
	AVE 3275	139.9	400	4310	740	5470	140.4	823
					825			
9	3400	140.9	660	6800	860	5250	142.1	1430
	3650	140.7	550	6490	840	6150	141.6	1240
	3900	141.1	560	7100	880	6400	140.8	1360
	AVE 3650	140.9	590	6800	850	5930	141.5	1343
					910			
10	4030	143.2	660	6300	930	7250	141.7	1060
	5390	142.9	750	7040	930	6800	141.6	1340
	4350	143.3	620	6100	940	7200	142.2	1110
	AVE 4590	143.1	630	6490	930	7120	141.8	1170

* Faulty Sample - Rebound

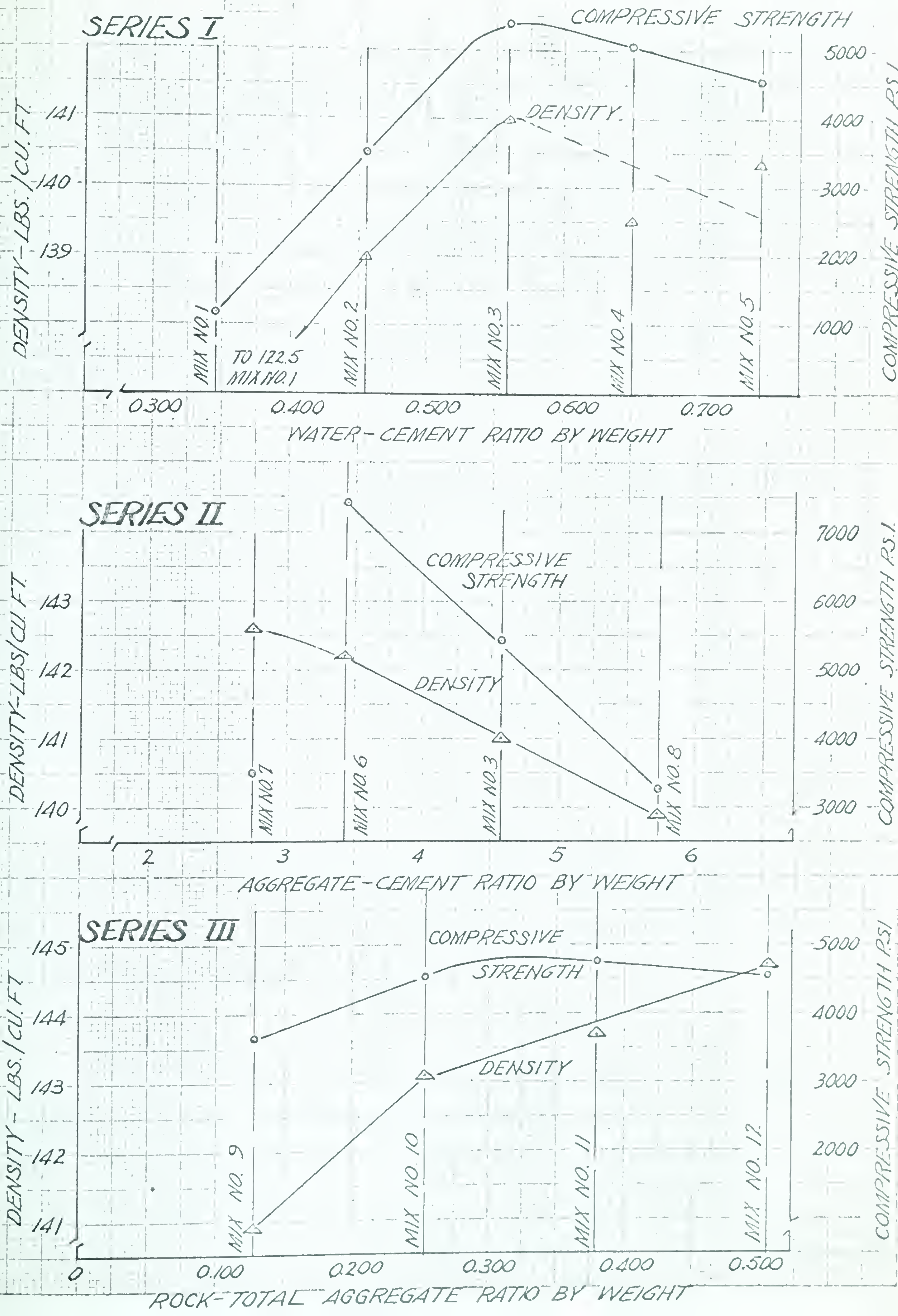
TABLE X

TEST RESULTS MIX NOS. 11 to 13 (28 DAY)

	6 in. by 12 in. CYLINDERS		COMPOSITE BEAMS		MONOLITHIC BEAMS			
Mix No.	Compressive Strength psi	Density lb per cu ft	Modulus of Rupture psi	Compressive Strength 4 in. Cubes psi	Modulus of Rupture psi	Compressive Strength 4 in. Cubes psi	Density 4 in. Cubes psi	Steel Bond Ultimate Stress psi
					990			
11	3650	143.3	705	6680	1000	6950	142.6	1240
	5890	144.4	695	7060	900	7100	142.5	1110
	2560*	143.3	560	6120	790	7050	142.7	1450
AVE	4770	143.7	650	6610	920	7030	142.6	1267
12	4260	144.5	120*	7000	770	7700	142.6	1270
	5430	145.1	400	7800	960	8450	143.3	1400
	4050	144.4	400	6950	825	7600	143.1	1570
AVE	4580	144.7	400	7250	850	7920	143.0	1413
13	3700	141.0	260*	6300	825	5650	142.3	1270
	4070	141.2	635	6840	840	4700	141.6	1140
	3680	141.0	550	5380		6300	142.3	1360
AVE	3820	141.1	590	6180	830	5550	142.1	1257

* Faulty Sample - Rebound

FIGURE NO. 18 COMPARISON OF COMPRESSIVE STRENGTHS AND DENSITIES OF 6" X 12" CYLINDERS



In Series II, (FIGURE 18), the consistency was held constant and the aggregate-cement ratio and water-cement ratio varied. Mix No. 7 was an exception here because the machine operator inadvertently added more water than was planned when loading the machine. The graph for Series II shows a decrease in compressive strength and density with an increase in the aggregate-cement ratio with the exception of Mix No. 7.

In Series III, the consistency and aggregate-cement ratio were held constant and the proportion of 3/8 in. aggregate was varied. The compressive strength increased to a maximum with a rock-total aggregate ratio of approximately 0.3 and decreased slightly with increasing amounts of rock. The density increased continuously with increased rock content.

In summary, the graphs in FIGURE 18 generally show the compressive strengths varying as the density with the exception of Series III where increasing amounts of 3/8 in. aggregate overrides this tendency.

FIGURES 19 and 20 show plots of compressive strength versus density of individual cylinders for each of the 13 mixes. Individual graphs were drawn because each mix has different batch proportions and thus different strength and

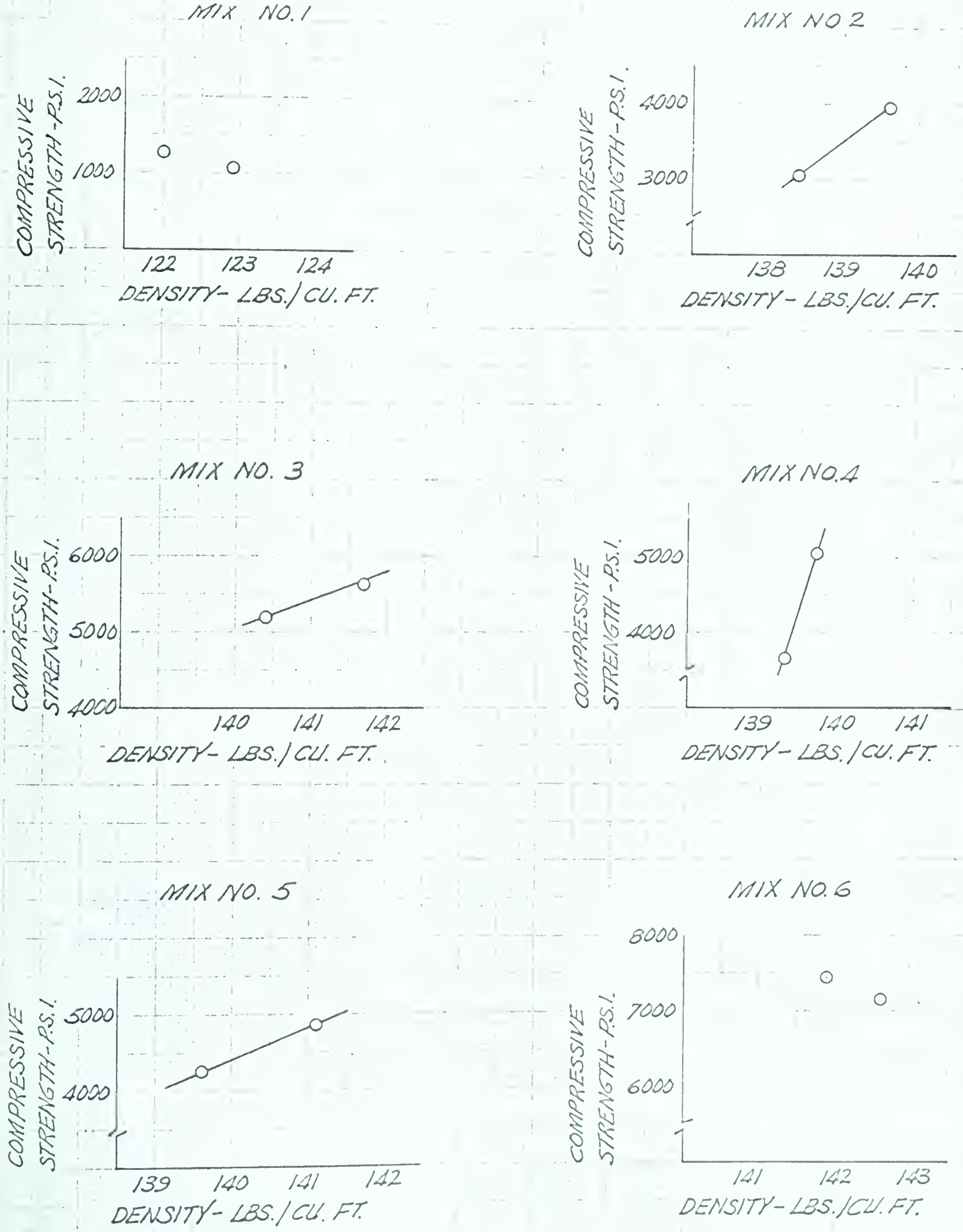


FIGURE NO. 19 PLOT OF 28 DAY COMPRESSIVE STRENGTH AGAINST DENSITY FOR 6" X 12" CYLINDERS

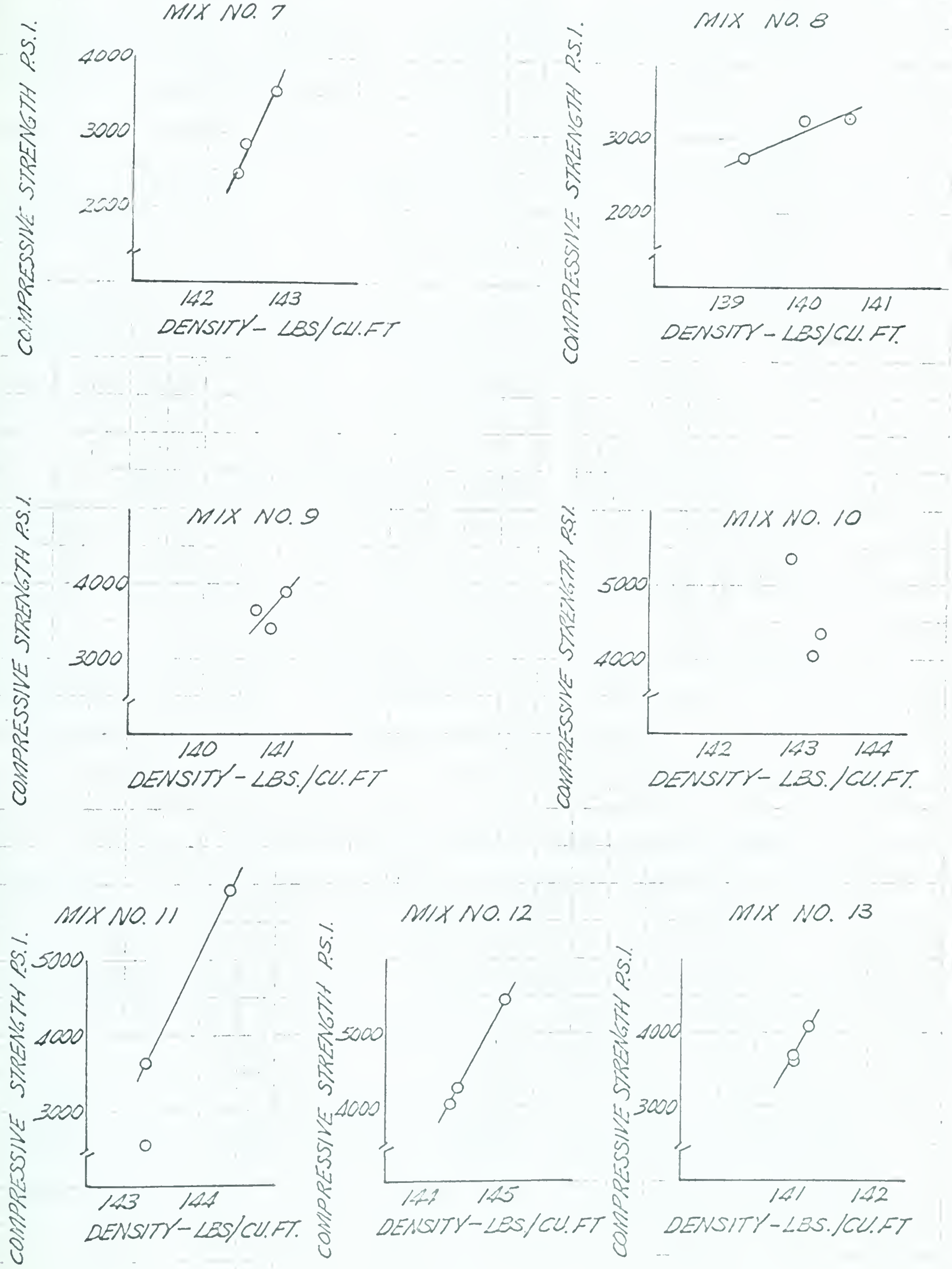


FIGURE NO. 20 PLOT OF 28 DAY COMPRESSIVE STRENGTH AGAINST DENSITY FOR 6" X 12" CYLINDERS

density characteristics. It is generally accepted that increasing the density of a particular concrete mix will increase the compressive strength, the void-cement ratio being a critical factor. The data available from this testing program was insufficient to establish any definite relationships, however, it is presented in this manner to show that there appears to be a trend. In this testing program, of course, the densities of the cylinders in each mix were not varied intentionally.

It is believed that the variation in density was a major cause of the variation in the compressive strength of the cylinders in any mix. These variations in density could have been caused by a number of factors such as incomplete mixing or segregation, varying nozzle velocity, or variations in the operation of the nozzle.

It is believed that a major cause of variation in densities lies in what will be called the "coning effect". This "coning effect" refers to the way in which the material builds up in the cylinder when it is shot. If the nozzle was directed towards the centre of the 6 in. diameter mold, the material would tend to build up in the centre faster than at the perimeter, and thus the cylinder would fill up with a rising conical surface. The material

then, to a large extent, would strike the surface at an angle substantially less than 90 degrees as is necessary for optimum compaction.

For these test specimens the nozzle operator moved the nozzle with a rotary motion in an attempt to decrease this "coning effect". Since the shooting time of one cylinder was approximately ten seconds, the operator had very little time to control the placing of the material. The visibility of the working surface inside the cylinder was limited and the confined working area restricted the nozzle movement.

EFFECT OF WATER-CEMENT RATIO ON FLEXURAL AND COMPRESSIVE STRENGTHS

FIGURE 21 shows the compressive strengths and moduli of rupture plotted against the water-cement ratio for Series I. The graph shows that the flexural strength of the monolithic beams followed a trend similar to the compressive strength curve, reaching a maximum at a water-cement ratio of approximately 0.56 (Mix No. 3). Mix Nos. 1 and 2 were too dry for optimum compaction and thus their strengths were lower. It is significant that the maximum compressive, flexural and steel bond strengths were attained

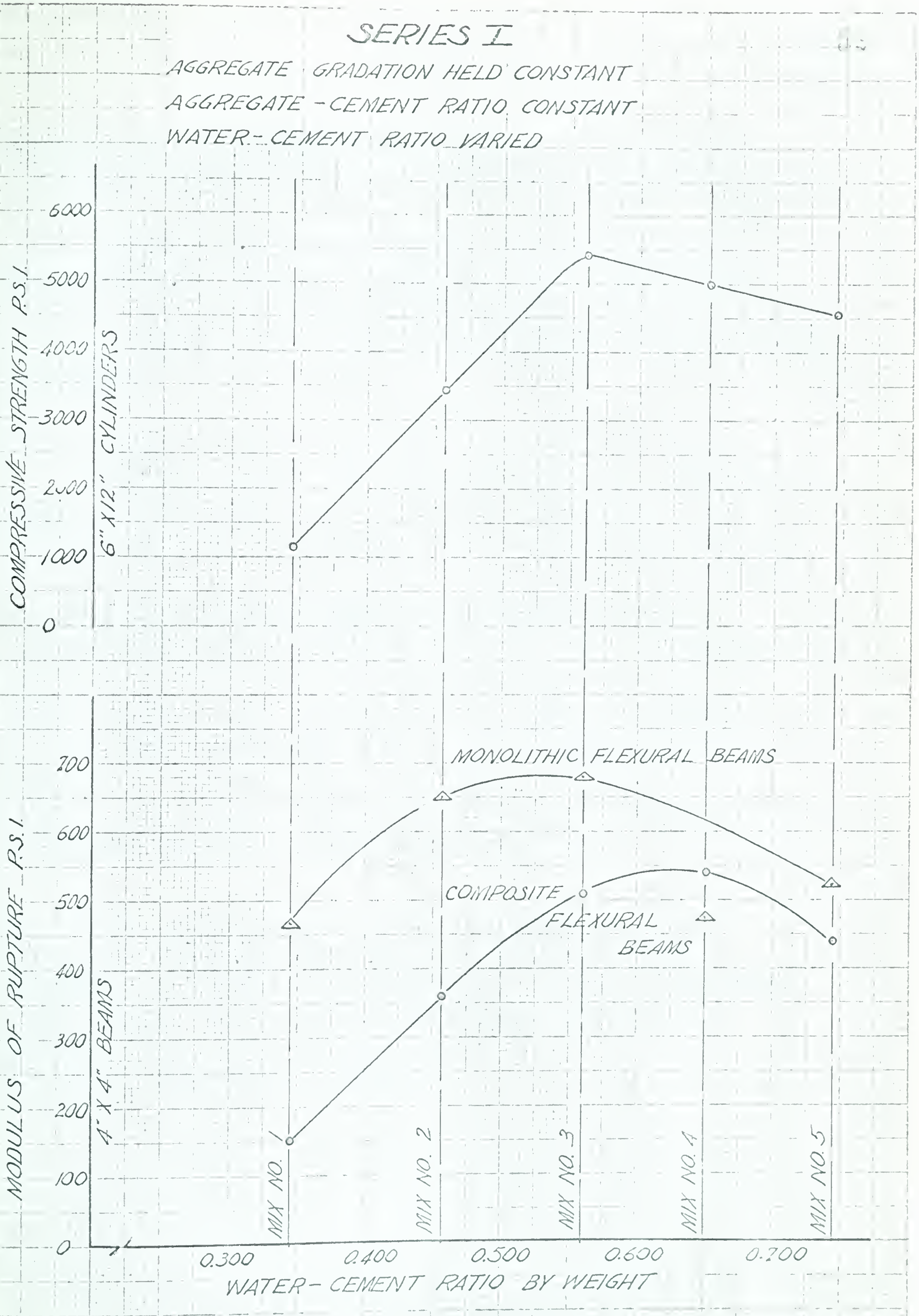


FIGURE NO. 21 FLEXURAL AND COMPRESSIVE STRENGTHS

with Mix No. 3, which was of a consistency meeting the previously described criteria used in field work. This field criteria refers primarily to the consistency at which shotcrete can most easily be placed. The test results indicate that this consistency also produces maximum strengths.

TABLE XI, shows that the failures of the composite beams for Mix Nos. 1, 2, 3 and 5 were generally a short distance from the joint. Thus the comparison of the beam strengths on FIGURE 21 may not actually be a true comparison of concrete to concrete bond. It is evident that for these cases the flexural strengths are greater for the beams which were shot in a horizontal position (monolithic beams) than for the beams which were shot in a vertical position using a metal mesh cage.

The composite beams reached a maximum flexural strength at a higher water-cement ratio than did the monolithic beams. The explanation probably lies in the different fabrication technique.

TABLE XI

FLEXURAL STRENGTH OF COMPOSITE BEAMS. - LOCATION OF FAILURE

MIX NO.	MODULUS OF RUPTURE psi	PORTION OF BREAK RIGHT AT JOINT % OF TOTAL AREA	PORTION OF BREAK AWAY FROM JOINT % TOTAL AREA	DISTANCE
1	60	0%	100%	$\frac{1}{2}$ in. - 2 in.
	340	0%	100%	$\frac{1}{2}$ in. - 1-$\frac{1}{2}$ in.
	40	0%	100%	2 in. - 1-$\frac{1}{2}$ in.
2	420	0%	100%	2 in.
	300	0%	100%	1 in.
	350	0%	100%	2 in.
3	500	0%	100%	2 in.
	480	50%	50%	0 in. - 1/8 in.
	550	0%	100%	2 in.
4	580	0%	100%	2 in.*
	440	50%	50%	0 in. - 1/8 in.
	600	50%	50%	0 in. - $\frac{1}{4}$ in.
5	480	0%	100%	$\frac{1}{2}$ in. - 1 in.
	520	0%	100%	$\frac{1}{2}$ in. - $\frac{1}{4}$ in.
	330	60%	40%	1/8 in.
6	500	100%	0%	0
	600	70%	30%	0 in. - 3/4 in.
	680	0%	100%	1 in. - 2 in.

* Failure in "old Concrete" Portion of Beam

EFFECT OF AGGREGATE-CEMENT RATIO WITH UNIFORM CONSISTENCY ON FLEXURAL AND COMPRESSIVE STRENGTHS

FIGURE 22 shows the compressive strengths, moduli of rupture and water-cement ratios plotted against the aggregate-cement ratio for Series II. For this series of tests the water-cement ratio was varied as well as the aggregate-cement ratio, in an attempt to hold the consistency of the mixes constant. Of these two variables, the water-cement ratio has the most significant effect on the strengths.

Mix No. 7 was made with the lowest aggregate-cement ratio. As previously discussed, this mix was accidently made with more mixing water than was planned for uniform consistency within the Series. The fact that it was wetter apparently did not greatly reduce the flexural strengths of the monolithic and composite beams in relation to the other mixes in this series, however, the 6 in. by 12 in. cylinder strength was relatively low. These inconsistent results for Mix No. 7 may be due to some undetected variation in equipment operation or shooting technique.

The flexural strengths of the monolithic beams for Series II were quite inconsistent, as can be seen in FIGURE 22. One would expect these results to show a decrease in strength with an increase in the aggregate-cement ratio because of the

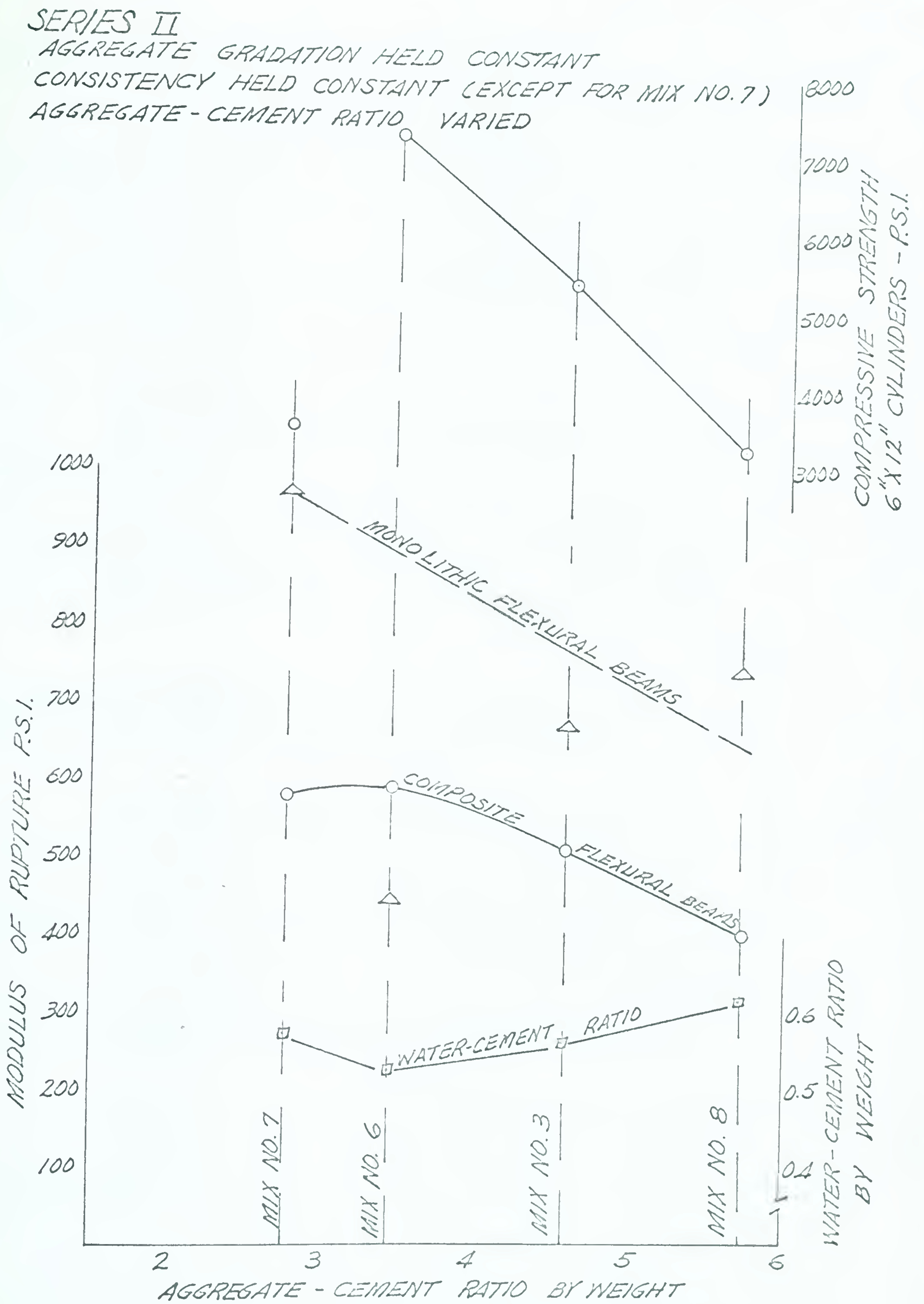


FIGURE NO. 22 FLEXURAL AND COMPRESSIVE STRENGTHS

corresponding increase in the water-cement ratio. However, the test results by themselves are too erratic to establish this trend. Mix No. 6 falls the farthest out of line. Here again, these large discrepancies may be due to some undetected variation in equipment operation or shooting technique.

With the exception of Mix No. 7, the composite beam flexural strength decreases as would be expected with the increase in aggregate-cement ratio, because of the corresponding increase in the water-cement ratio.

EFFECT OF AGGREGATE GRADATION ON STRENGTHS

For Series III the total aggregate-cement ratio and the consistency were held constant while the aggregate gradation was varied. With increasing proportions of the 3/8 in. crush aggregate, the water-cement ratio was reduced to maintain a uniform consistency.

FIGURE 23 shows the water-cement ratio, the compressive strengths of the 6 in. by 12 in. cylinders and the flexural strengths of the monolithic and composite beams plotted against the 3/8 in. crush aggregate-total aggregate ratio.

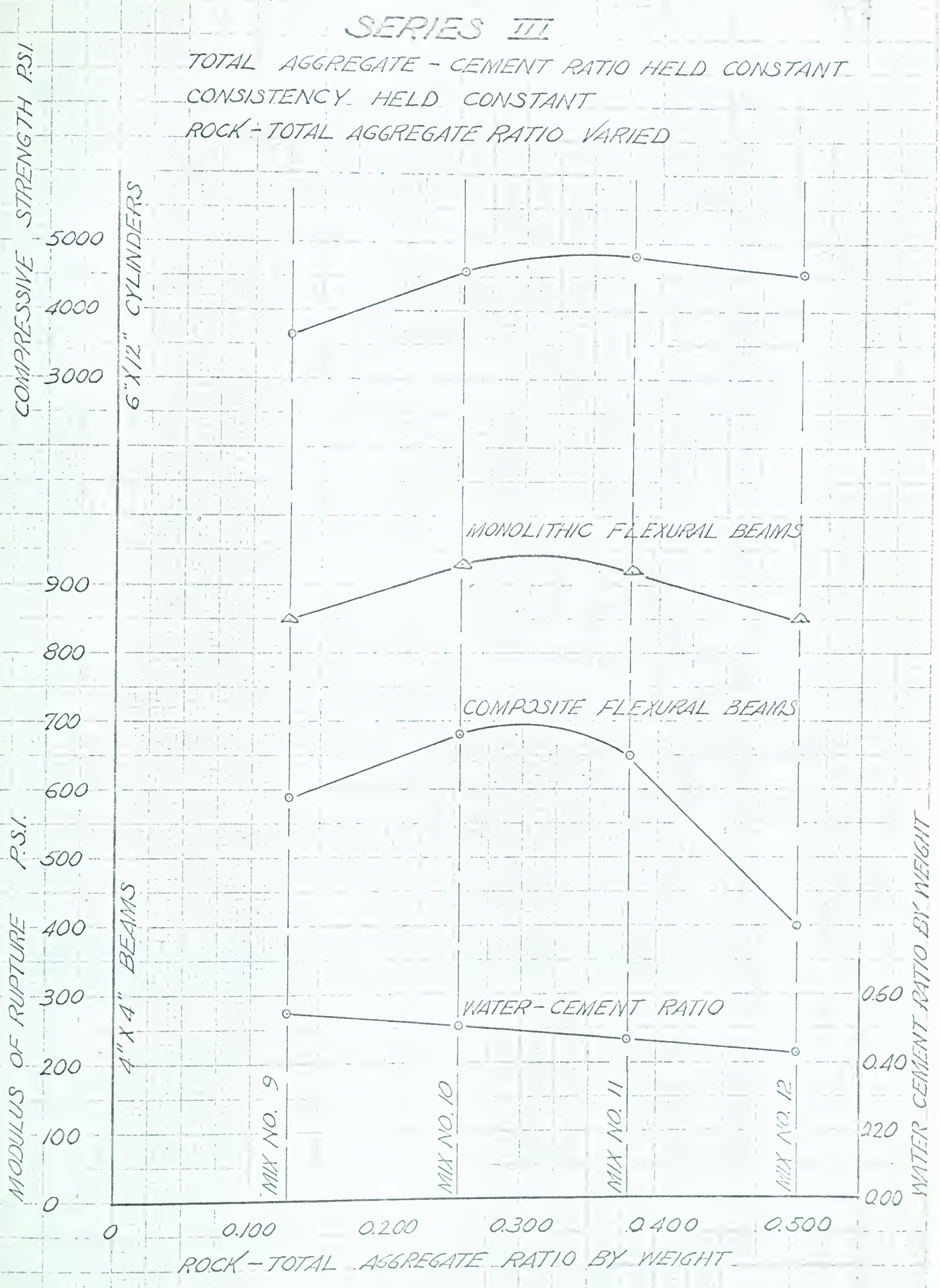


FIGURE NO. 23 FLEXURAL AND COMPRESSIVE STRENGTHS

Each point shown on the strength curves is the average value of three test specimens. The results for this series all fell on smooth curves with maximum strengths at a 3/8 in. crush aggregate-total aggregate ratio of approximately 0.3. The decreasing water-cement ratio would tend to cause a corresponding increase in strength but apparently the factor which overrides this tendency in Mix Nos. 11 and 12 is that the higher proportions of 3/8 in. material in the mixes made them too harsh for optimum compaction and optimum strength.

For Mix No. 12, the composite beam strength dropped correspondingly more than the monolithic beam strength and the cylinder strength. This indicates that excessive amounts of coarser aggregate reduced the concrete to concrete bond to a larger degree than it reduced the flexural and compressive strengths.

COMPRESSIVE STRENGTH OF 4 in. CUBES COMPARED WITH COMPRESSIVE STRENGTHS OF 6 in. by 12 in. CYLINDERS

FIGURE 24 shows the compressive strengths of 4 in. cubes cut from the monolithic beams and the composite beams plotted against the corresponding compressive strengths of 6 in. by 12 in. cylinders. Each point plotted was the average of three test specimens. Separate points were used

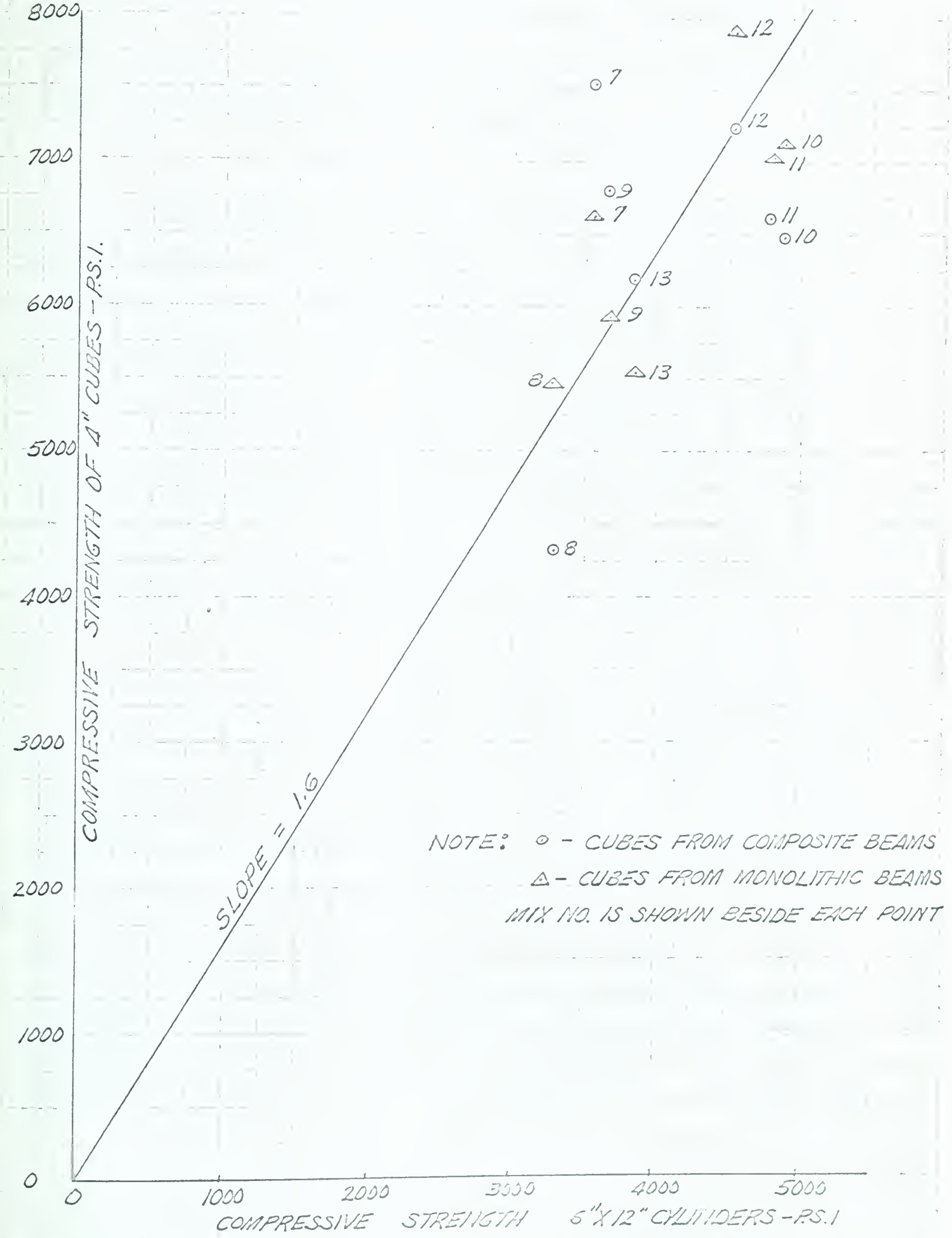


FIGURE NO. 24 COMPRESSIVE STRENGTHS - COMPARISON OF 4" CUBES AND 6" X 12" CYLINDERS

for the cubes obtained from the composite beams and from the monolithic beams. The best fitting straight line was drawn by eye through these points to zero.

For Mix Nos. 8, 10, 11 and 12, the cubes from the monolithic beams gave higher strengths than the cubes from the composite beams, while for Mix Nos. 7, 9 and 13, the cubes from the composite beams gave the higher strengths. From this it appears that there is no trend as to which method of shooting the cubes gives higher cube strengths. Apparently there was no "coning effect" for the composite beams, possibly because the spray from the nozzle was almost as large as the 4 in. mold.

The slope of the line in FIGURE 24 shows the ratio of the 4 in. cube strengths to the 6 in. by 12 in. cylinder strengths to be 1.6. There are several reasons for the 4 in. cubes giving higher compressive strengths than the 6 in. by 12 in. cylinders. The first factor is the shape of the specimens. Cylinders with length-diameter ratio of 1:1 have compressive strengths about 18% greater than the standard cylinder with a length-diameter ratio of 2:1, and this factor of 1.18 is roughly applicable to cubes (10).

The second factor is that of size of compression specimen. It has been shown that 2 in. by 4 in. cylinders have strengths 9% greater than 6 in. by 12 in. cylinders, and also 3 in. by 6 in. cylinders have strengths 6% greater than 6 in. by 12 in. cylinders (11). From this it appears that the size factor (for 4 in. cubes) would cause a strength increase of 6% to 8% over that of the 6 in. by 12 in. cylinders. From these considerations, it appears that the combined effects of the size and shape factors is that the 4 in. cube strengths should be in the order of 25% greater than the 6 in. by 12 in. cylinder strengths, however, in this testing program, the cube strengths were 60% greater. The difference may be due to some difference in the quality of the cubes and cylinders. Since the specimens were all broken shortly after their removal from the moist room, the moisture conditions were similar. It is believed that what has been previously described as the "coning effect" encountered in shooting the cylinders may be a major cause of the lower cylinder strengths.

RANGE OF COMPRESSIVE STRENGTHS FOR EACH GROUP OF THREE SPECIMENS

TABLE XII summarizes the compressive strength results for Mix Nos. 7 to 13 inclusive. The average strength and the range of each group of 3 specimens is shown.

TABLE XII

RANGE OF COMPRESSIVE STRENGTHS FOR EACH GROUP OF 3 SPECIMENS

Mix No.	6 in. by 12 in. CYLINDERS Compr. Str. psi	Average	Range	4 in. CUBES FROM COMPOSITE BEAMS Compr. Str. psi	Average	Range	4 in. CUBES FROM MONOLITHIC BEAMS Compr. Str. psi	Average	Range
7	2850			7250			6250		
	3540			7550			6650		
	2470	2950	1070	7600	7540	350	6950	6620	700
8	3300			4280			4800		
	2750			3850			6200		
	3250	3100	550	4780	4310	930	5400	5470	1400
9	3400			6800			5250		
	3650			6490			6150		
	3900	3650	500	7100	6800	610	6400	5930	1150
10	4030			6300			7250		
	5390			7040			6800		
	4350	4590	1360	6100	6490	940	7300	7120	500
11	3650			6680			6950		
	5890			7060			7100		
	2560	4030	3330	6120	6610	940	7050	7030	150
12	4260			7000			7700		
	5430			7800			8450		
	4050	4580	1380	6950	7250	850	7600	7920	850
13	3700			6300			5650		
	4070			6840			4700		
	3680	3820	390	5380	6180	460	6300	5550	1600

NOTE: The "Range" is the difference between the highest and lowest of the three specimens.

Considering each type of specimen in turn, there is considerable variation in the ranges for the different mixes, with no particular trend evident. From the data available, it can not be established which type of compressive specimen could be expected to have the lowest within test variation. It may be noted that the cylinder strength range for Mix No. 13 (Gunite) was lower than that of the other mixes, however this data is insufficient to conclude that the cylinder within test variations for Gunite can be expected to be lower than that of Gun-All.

COMPARISON OF MONOLITHIC BEAM FLEXURAL STRENGTHS AND COMPRESSIVE STRENGTHS

FIGURE 25 shows flexural strengths plotted against the corresponding 4 in. cube strengths for Mix Nos. 7 to 13. Each point plotted was the average of three test specimens and the best fitting straight line was drawn through these points to the origin.

The generally accepted relationship is a slightly curved line with a steeper slope for lower strengths (12). For this plot, there are no test results in the lower range, so this curve could not be established. The slope of the best fitting straight line is 0.14, and the range is from 0.11 to 0.15.

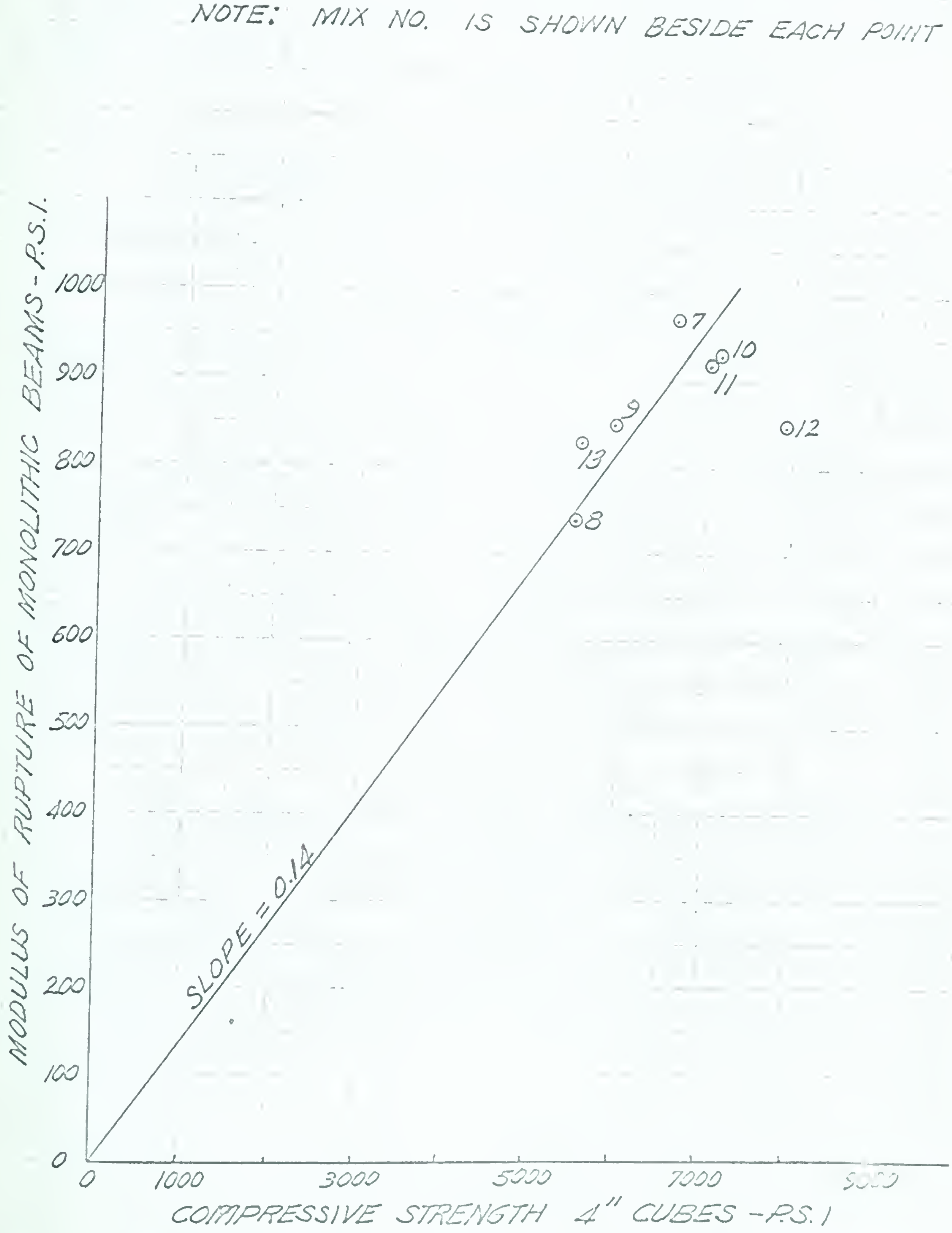


FIGURE NO. 25 MONOLITHIC BEAMS - COMPARISON OF MODULUS OF RUPTURE AND COMPRESSIVE STRENGTH OF 4" CUBES

The points all fell quite close to the best fitting line with the exception of Mix No. 12 which was lower. Since Mix No. 12 contained the highest proportion of 3/8 in. crush aggregate, this indicates that excessive proportions of the coarse aggregate affected the flexural strength more than the compressive strength of the cubes.

In FIGURE 26 the flexural strength was plotted against the compressive strength of the 6 in. by 12 in. cylinders. The slope of the best fitting straight line is 0.19. The points for Mix Nos. 4 and 6 fall the farthest from this best fitting straight line and it will be shown later in the comparison of flexural strength and composite beam strength that these flexural strengths for Mix Nos. 4 and 6 were unreasonably low. Excluding Mix Nos. 4 and 6, and also Mix No. 1 which was excessively dry, the range for this relationship is from 0.11 to 0.27.

The modulus of rupture ranges from 11% to 23% of the compressive strengths for normal concretes (13) and these results indicate the modulus of ruptures of shotcrete to be a comparable percentage of compressive strength.

NOTE: MIX NO. IS SHOWN BESIDE EACH POINT

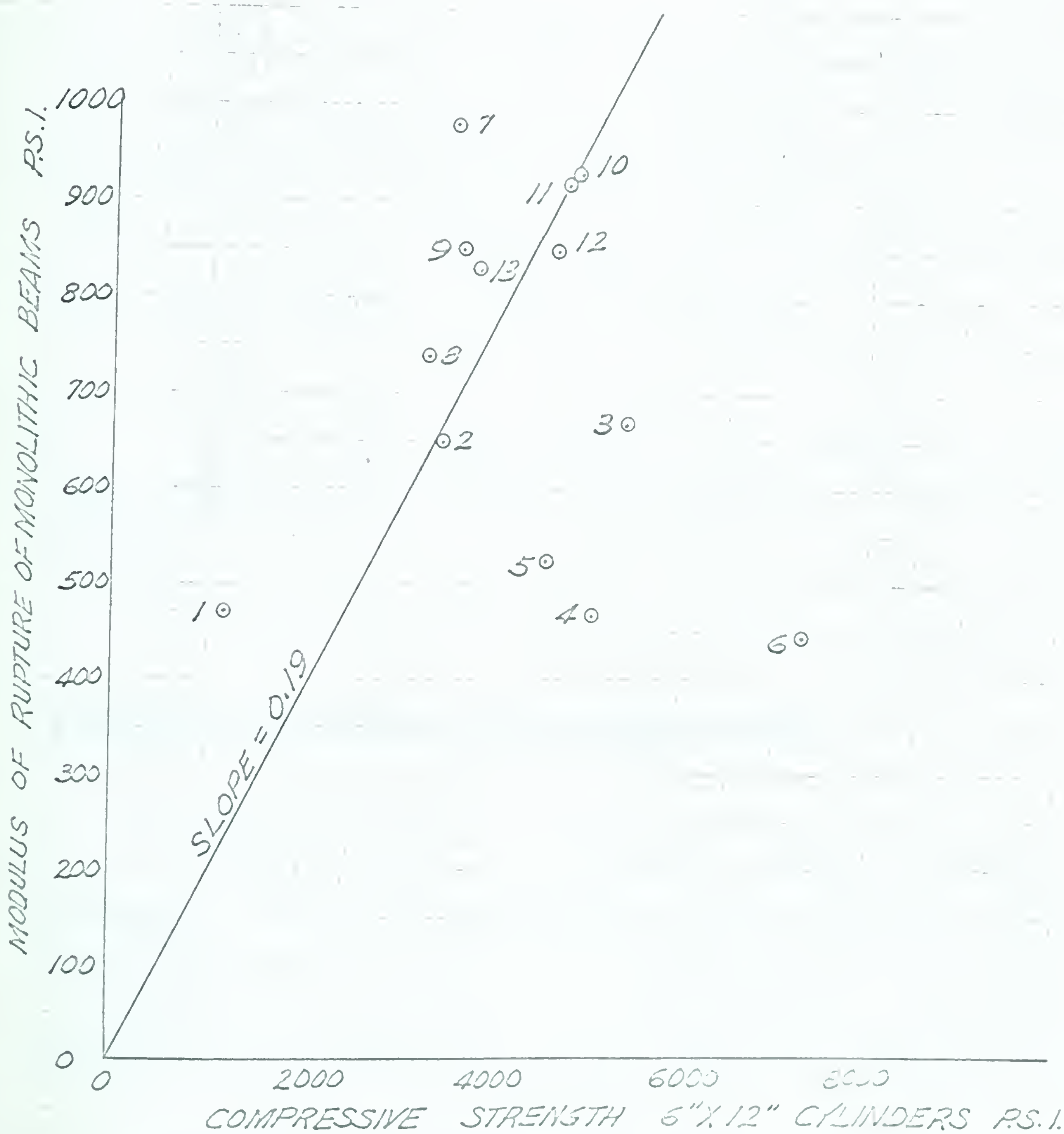


FIGURE NO. 26 COMPARISON OF MODULUS OF RUPTURE OF MONOLITHIC BEAMS AND COMPRESSIVE STRENGTH 6"X12" CYLS.

CONCRETE TO CONCRETE BOND SPECIMENS (COMPOSITE BEAMS)

The concrete to concrete bond specimens consisted of composite 4 in. by 4 in. beams which were broken in flexure. TABLES XI and XIII show the moduli of rupture and also the location of the failure relative to the joint between the "old concrete" portion and the shot portion of each beam.

In most cases failure was at or very near the joint with some exceptions, notably in Mix Nos. 1, 2, 3 and 5. In these cases, the breaks occurred from 1/4 in. to 2 in. from the joint, indicating that the joints for these beams were just as strong as the shot portion.

In the succeeding pages of this chapter, the composite beam strengths will be compared with various other strength values.

FLEXURAL STRENGTHS OF THE COMPOSITE BEAMS

FIGURE 27 shows the modulus of rupture of the composite beams plotted against the corresponding compressive strengths of 4 in. cubes which were cut from the "shot" portion of the composite beams. Each point plotted is the

TABLE XIII

FLEXURAL STRENGTH OF COMPOSITE BEAMS.-LOCATION OF FAILURE

MIX NO.	MODULUS OF RUPTURE psi	PORTION OF BREAK RIGHT AT JOINT % OF TOTAL AREA	PORTION OF BREAK AWAY FROM JOINT % TOTAL AREA	DISTANCE
7	460	70%	30%	0 in. - 1/8 in.
	620	50%	50%	0 in. - 1/8 in.
	650	50%	50%	0 in. - 1/8 in.
8	410	50%	50%	0 in. - 1/8 in.
	410	50%	50%	0 in. - 1/8 in.
	380	60%	40%	1/16 in. - ½ in.
9	660	50%	50%	0 in. - 1/8 in.
	550	30%	70%	0 in. - 1/8 in.
	560	50%	50%	1 in. - ½ in.
10	660	50%	50%	0 in. - 3/4 in.
	750	50%	50%	¼ in. - 1 in.
	620	25%	75%	0 in. - ¼ in.
11	705	40%	60%	0 in. - [illegible] in.
	695	50%	50%	0 in. - ¼ in.
	560	100%	0%	
12	120	100%	0%	
	400	50%	50%	0 in. - ¼ in.
	400	100%	0%	
13	260	100%	0%	
	635	80%	20%	0 in. - ¼ in.
	550	50%	50%	0 in. - ¼ in.

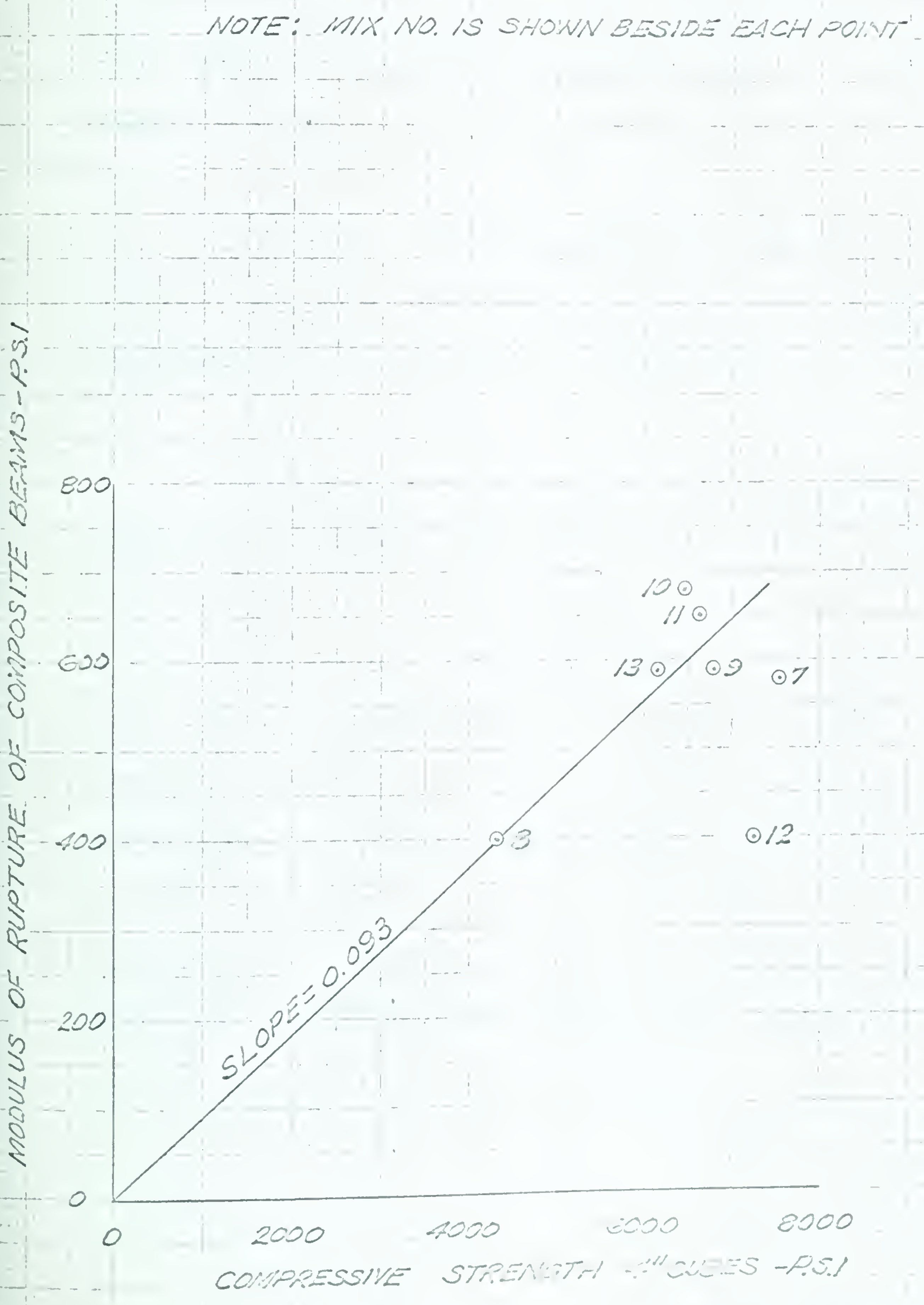


FIGURE NO. 27 COMPOSITE BEAMS – COMPARISON OF MODULUS OF RUPTURE AND COMPRESSIVE STRENGTH 4" CUBES

average of 3 test specimens. The slope of the best fitting straight line is 0.093, and with the exception of Mix No. 12, the points all fall quite closely to this line. Since Mix No. 12 contained the highest proportion of 3/8 in. crush aggregate, this indicates that excessive amounts of this aggregate in the mix decreased the concrete to concrete bond.

Since the composite beams for Mix Nos. 7 to 13 broke at or very near the joint, the results may be considered to be a measure of the concrete to concrete bond.

For Mix Nos. 1, 2, 3 and 5, the failures of the composite flexural beams were mainly not at the joint, but from 1/4 in. to 2 in. from the joint in the "shot" proportions of the composite beams. Thus for these mixes, the composite beam modulus of rupture is more a measure of flexural strength for this particular method of fabrication, than a measure of the concrete to concrete bond strength. In the remaining mixes, that is Mix Nos. 4 and 6 to 13 inclusive, the failures were at or very near the joint. Thus for these mixes the results are a measure of the concrete to concrete bond strengths.

FIGURE 28 shows the composite beam flexural strength plotted against the monolithic beam flexural strength. The composite beam strengths for Mix Nos. 4 and 6 were greater than the corresponding monolithic beam strengths. In all of the previously discussed comparisons of the monolithic beam flexural strengths (FIGURES 21, 22 and 26), the values for Mix Nos. 4 and 6 fell lower than the general trends would indicate. These considerations all indicate that the quality of the monolithic beams for these two mixes was lower than should be expected. Mix No. 1, which was excessively dry, fell the furthest below the best fitting straight line. The slope of the best fitting straight line is 0.67, and with the exceptions of Mix Nos. 1 and No. 3 to No. 6 inclusive, the range is from 0.47 to 0.75.

The larger proportion of 3/8 in. aggregate in Mix No. 12 appears to have caused some reduction in the concrete to concrete bond strength.

REINFORCING STEEL BOND TEST RESULTS

TABLES XIV and XV show the results of the steel bond tests. It will be noted from the table that in Mix Nos. 2 to 6 where No. 4 bars were used, almost all of the reinforcing

NOTE: MIX NO. IS SHOWN BESIDE EACH POINT

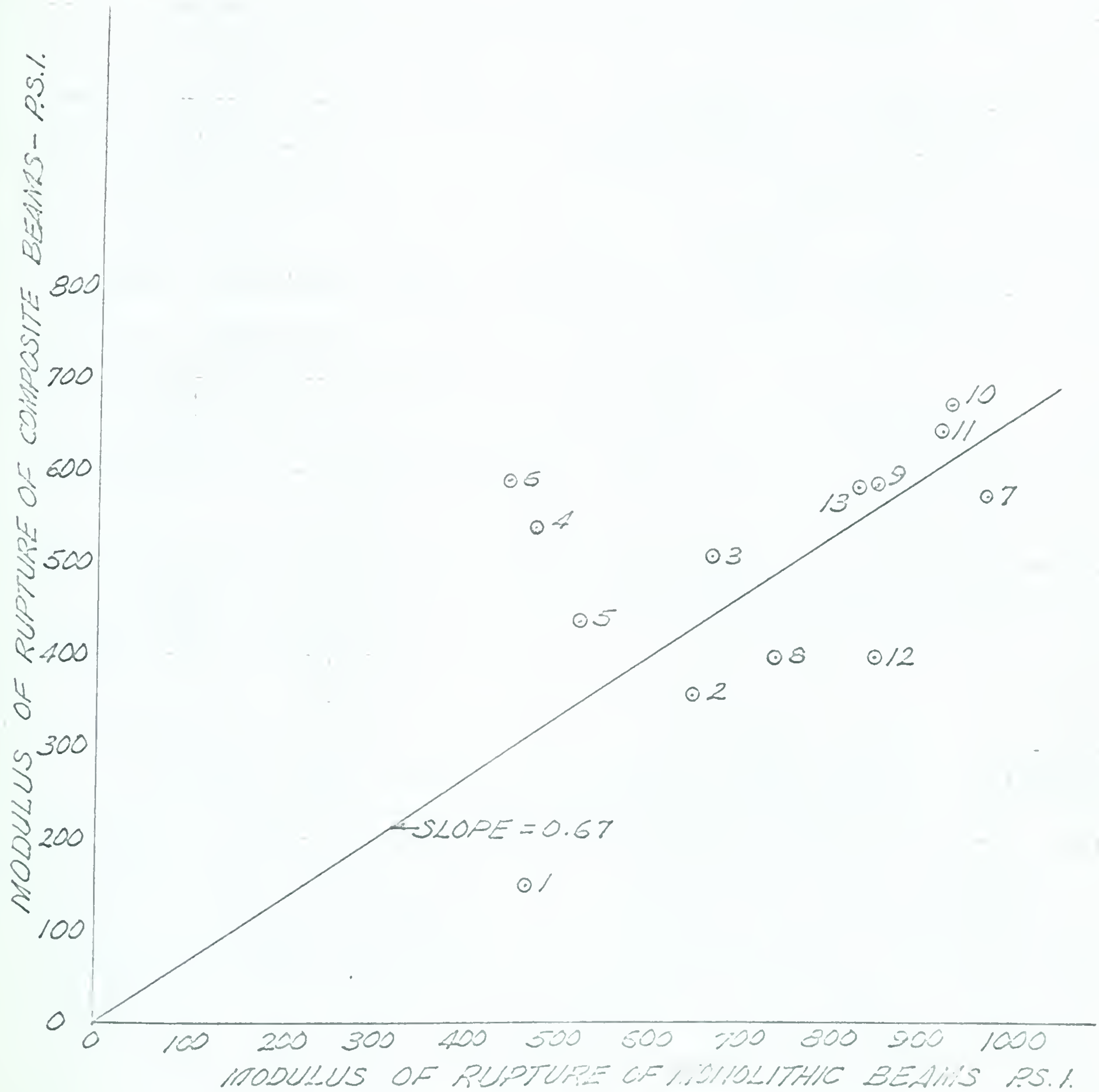


FIGURE NO. 28 COMPARISON OF COMPOSITE BEAM AND MONOLITHIC BEAM STRENGTHS

bars yielded before the ultimate load was reached. In all cases there was no measurable slip at the free end of the reinforcing bars and with only two exceptions failure was due to the 6 in. cubes splitting in two, three or four sections. For Mix Nos. 7 to 12 where No. 6 bars were used with 6 in. cubes of concrete, in only one test specimen did the reinforcing bar yield.

The extents of the voids which were evident beneath the reinforcing bar after the concrete blocks were broken in testing are outlined in TABLES XIV and XV. For Mix No. 1, previously described as being excessively dry, it was evident from the broken sections that the concrete was poorly compacted and contained rebound sand. For Mix No. 2, which was also a dry mix, there were voids under the reinforcing bar approximately 1/16 in. by 1/8 in. by 2 in. in each of the three specimens. In five of the remaining 33 steel bond specimens there was also evidence of voids under the reinforcing steel.

These test results actually do not give a true measure of the ultimate reinforcing steel bond stress because, with only two exceptions, failure occurred with the enclosed concrete cubes splitting. For this reason, as well as the fact that there was no measurable free end slip, it may be

TABLE XIV

STEEL BOND TEST RESULTS

MIX NO.	BAR SIZE	VOIDS UNDER BAR	ULTIMATE LOAD lb	ULTIMATE LOAD psi STEEL AREA	TYPE OF FAILURE
1	#4	Nil	4,050	430	C.S.
		Nil	5,950	630	C.S.
		Nil	6,800	720	PULL OUT
			AVE.	593	
2	#4	Nil	9,250	980	PULL OUT
		2 in. x 1/6 in. x 1/16 in.	10,100	1,070 Y	C.S.
		2 in. x 1/8 in. x 1/16 in.	9,950	1,060 Y	C.S.
			AVE.	1,037	
3	#4	Nil	13,900	1,470 Y	C.S.
		Nil	14,200	1,510 Y	C.S.
		Nil	13,800	1,460 Y	C.S.
			AVE.	1,480	
4	#4	Nil	12,050	1,280 Y	C.S.
		Nil	14,100	1,500 Y	C.S.
		Nil	13,000	1,380 Y	C.S.
			AVE.	1,387	
5	#4	1/2 in. x 1/16 in. x 1/16 in	9,300	990	C.S.
		Nil	9,950	1,060 Y	C.S.
		Nil	11,300	1,200 Y	C.S.
			AVE.	1,083	
6	#4	3 in. x 1/16 in. x 1/16 in.	10,700	1,140 Y	C.S.
		Nil	12,100	1,280 Y	C.S.
		Nil	12,100	1,280 Y	C.S.
			AVE.	1,233	
7	#6	2 in. x 1/8 in. x 1/16 in.	15,700	1,110	C.S.
		Nil	13,400	950	C.S.
		1-1/2 in. x 1/8 in. x 1/16 in.	14,300	1,010	C.S.
			AVE.	1,023	

NOTE: "Y" Means Steel Yielded Before Concrete Cube Split

"C.S." Means Concrete Cube Split

TABLE XV

STEEL BOND TEST RESULTS

MIX NO.	BAR SIZE	VOIDS UNDER BAR	ULTIMATE LOAD lb	ULTIMATE LOAD psi STEEL AREA	TYPE OF FAILURE
8	#6	Nil	11,300	800	C.S.
		Nil	11,100	790	C.S.
		Nil	12,500	800	C.S.
			AVE.	823	
9	#6	Nil	20,200	1,430	C.S.
		Nil	17,500	1,240	C.S.
		Nil	19,200	1,360	C.S.
			AVE.	1,343	
10	#6	Nil	15,000	1,060	C.S.
		Nil	19,000	1,340	C.S.
		Nil	15,700	1,110	C.S.
			AVE.	1,170	
11	#6	3 in. x 1/8 in. x 1/16 in.	17,500	1,240	C.S.
		Nil	15,700	1,110	C.S.
		Nil	20,500	1,450	C.S.
			AVE.	1,267	
12	#6	Nil	18,000	1,270	C.S.
		Nil	19,800	1,400	C.S.
		Nil	22,200	1,570 Y	C.S.
			AVE.	1,413	
13	#4	Nil	12,000	1,270 Y	C.S.
		Nil	10,700	1,140 Y	C.S.
		Nil	12,800	1,360 Y	C.S.
			AVE.	1,257	

NOTE: "Y" Means Steel Yielded Before Concrete Cube Split

"C.S." Means Concrete Cube Split

that the actual ultimate steel bond stress would be higher than the values obtained. In the analysis of these results, however, the term ultimate steel bond stress was used for simplification. Direct comparisons with published data for normal concretes may not be true comparisons, since 6 in. cubes of shotcrete were used rather than the standard 9 in. cubes.

FIGURE 29 shows the ultimate steel bond stress plotted against the compressive strength of the 6 in. by 12 in. cylinders with the best fitting straight line drawn through the points to zero on the graph. It has been reported that there is not a consistent relationship between steel bond strength and compressive strength of concrete, however, it has also been customary to specify permissible bond stresses as percentages of the compressive strength of concrete (14). The points on the graph, each the average of three test specimens, all fall reasonably close to the best fitting straight line with the exception of Mix No. 6. Since an equal number of points fall above and below the average line for both the No. 4 bars and the No. 6 bars, it appears that the ultimate steel bond stress is independent of the bar size for the ranges encountered.

The slope of the best fitting straight line is 0.275. The range of this relationship is from 0.22 to 0.36.

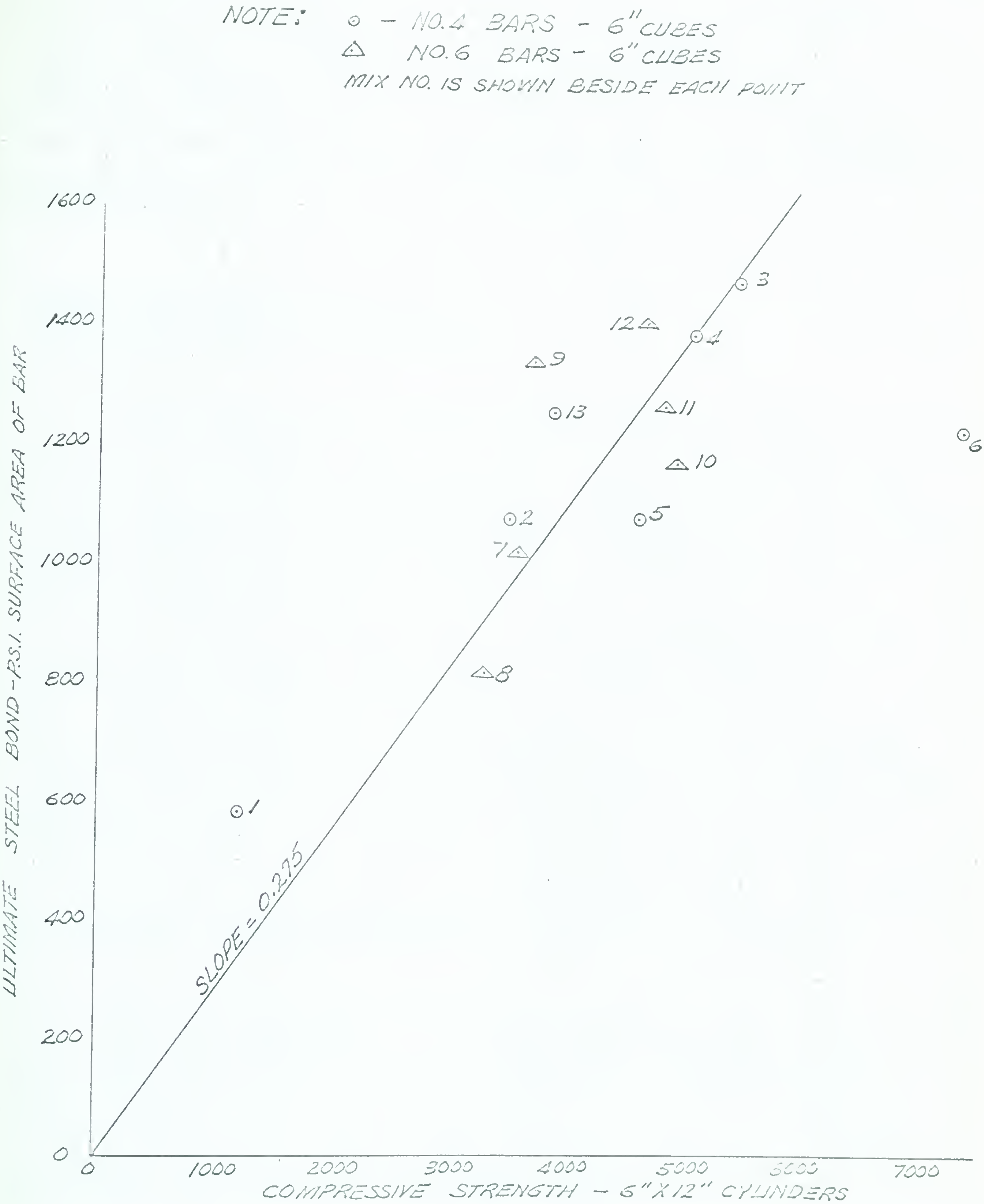


FIGURE NO. 29 COMPARISON OF STEEL BOND AND COMPRESSIVE STRENGTH OF 6" X 12" CYLINDERS

The results indicate that for most of the shotcrete mixes tested, the ultimate steel bond was 1000 psi or greater. Mix No. 1 which was excessively dry, and Mix No. 8 which was the leanest mix tested, both fell below this value of 1000 psi.

GUNITE TEST RESULTS (MIX NO. 13)

The test results for the Gunite specimens (Mix No. 13) are shown in TABLES X, XIII and XV. It is difficult to make a true comparison between the Gunite mix and any of the Gun-All mixes because the equipment set-up was entirely different. Since the Gunite mix had no equivalent in any of the twelve Gun-All mixes, direct comparisons of strengths can not be made. However, strength relationships such as cube strength versus cylinder strength, flexural strength versus compressive strength, and so on, do provide some basis for comparison. The various Gunite strength relationships are shown along with the Gun-All results on FIGURES 20, and 24 to 29 inclusive.

In the comparison of the compressive strength of the 4 in. cubes with 6 in. by 12 in. cylinders (FIGURE 24) the Gunite results fall close to the best fitting line, and they are within the range of the Gun-All mixes.

In the comparisons of the flexural strengths of the monolithic beams with the compressive strengths of the cubes and cylinders, (FIGURES 25 and 26) the Gunite results lie only slightly higher than the best fitting lines. In the comparison the composite beam flexural strength versus compressive strength of cubes the Gunite results again fall very close to the best fitting line (FIGURE 27).

In the comparison of flexural strengths of the composite beams with the monolithic beams (FIGURE NO. 28), the Gunite results are just slightly higher than the best fitting line for all of the tests.

In the steel bond versus compressive strength comparison (FIGURE 29) the Gunite results fall higher than the best fitting line but are still within the range of the other tests.

In summary, the above noted comparisons show that the Gunite strength relationships fall within the range of the Gun-All results.

EXPANSION UNDER CONTINUOUS MOIST CONDITIONS

Appendix B shows the linear change data obtained in this program. Temperature corrections were made assuming a thermal coefficient of 6 by 10^{-6} per degree F.

FIGURES 30 to 41 inclusive show the test results for the linear change specimens which were subjected to continuous moist storage conditions for approximately two years. During this time the specimens all expanded from 100 to 300 millionths, a range comparable to that of normal concrete which has been reported to be from 200 to 300 millionths (15).

The two year expansions for the different mixes do not fall into any particular patterns for the three series of tests.

GENERAL DISCUSSION OF RESULTS

In the analyses of the results of this testing program, various trends were established for the different strength relationships, and have been discussed in turn in this chapter. It should be noted that these trends pertain only to the specific conditions as outlined for

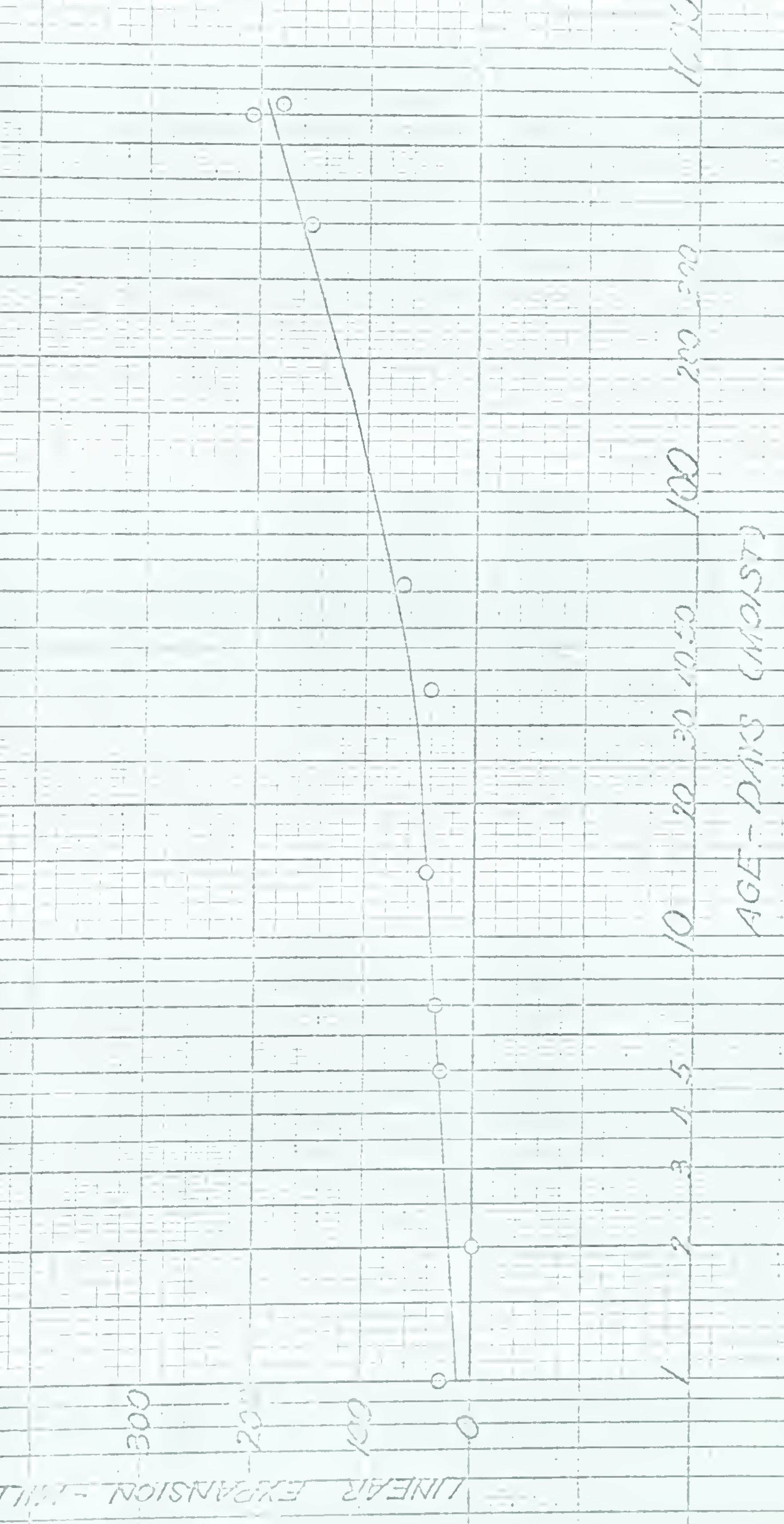


FIGURE NO. 30 LINEAR EXPANSION MIX NO. [illegible]

FIGURE NO. 37 LINEAR EXPANSION MIX NO. 2

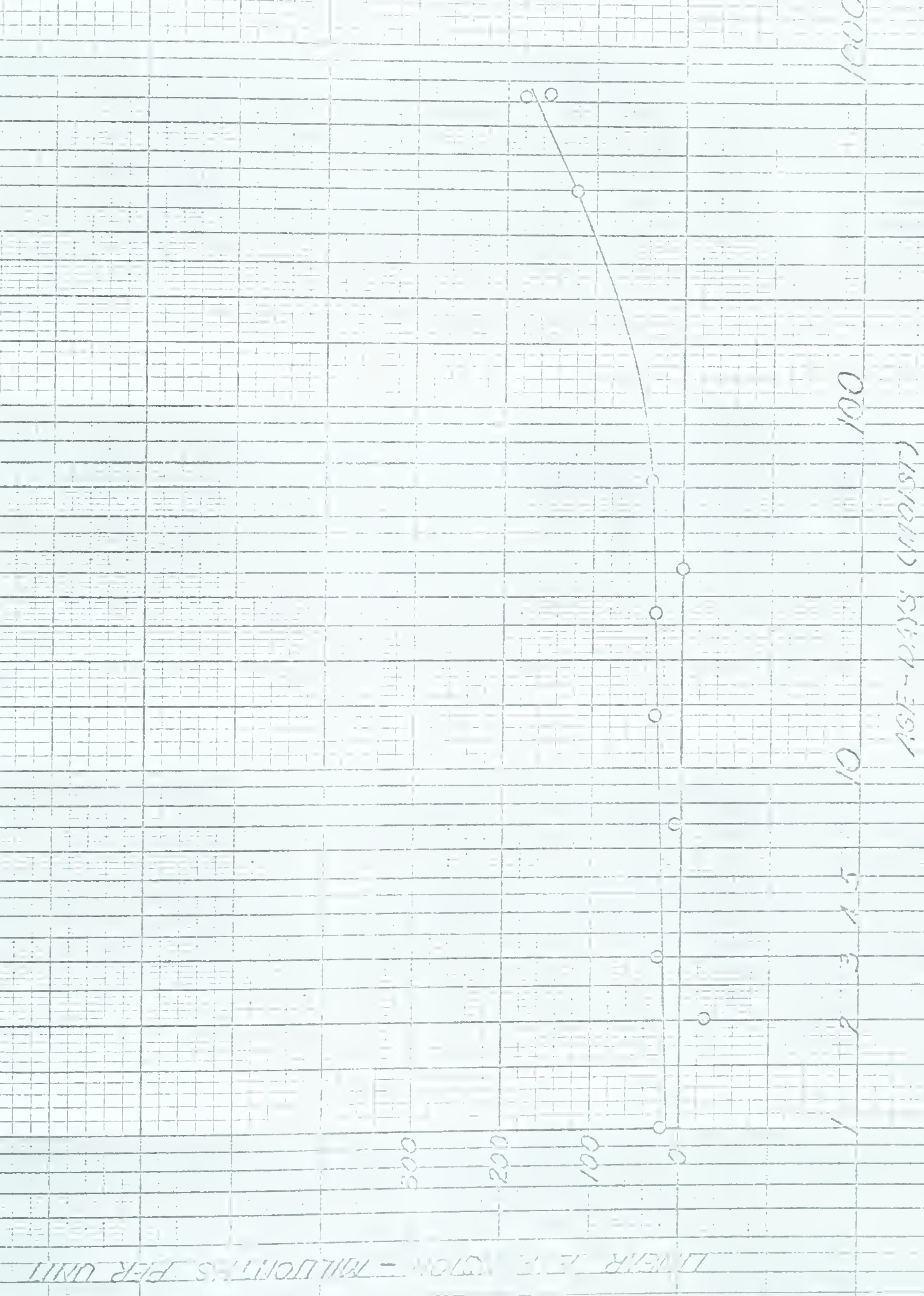


FIGURE NO. 32 LINEAR EXPANSION MIX NO. 3

FIGURE NO. 33 LINEAR EXPANSION [illegible]

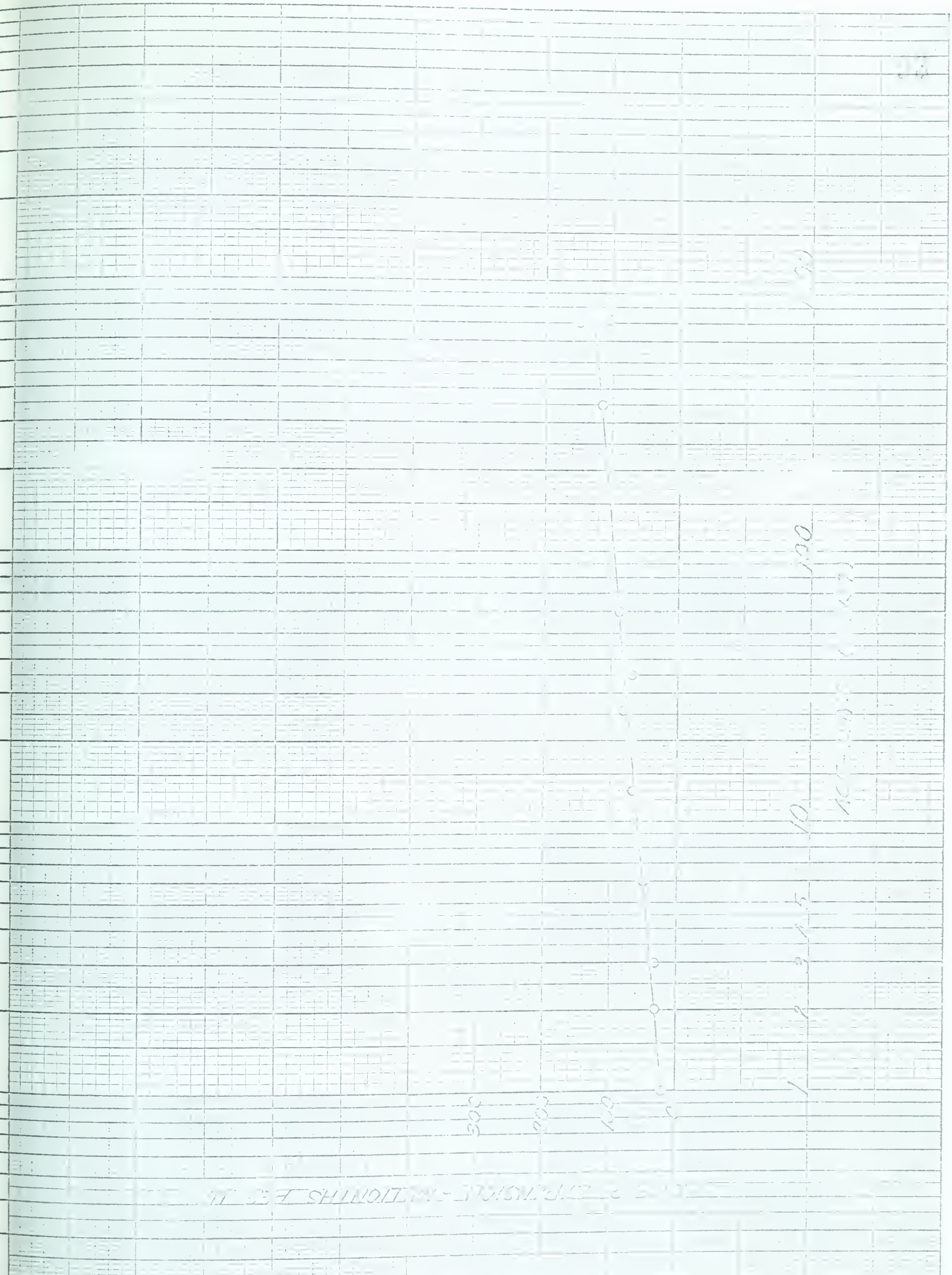


FIGURE NO. 34 — LINEAR EXP [illegible]

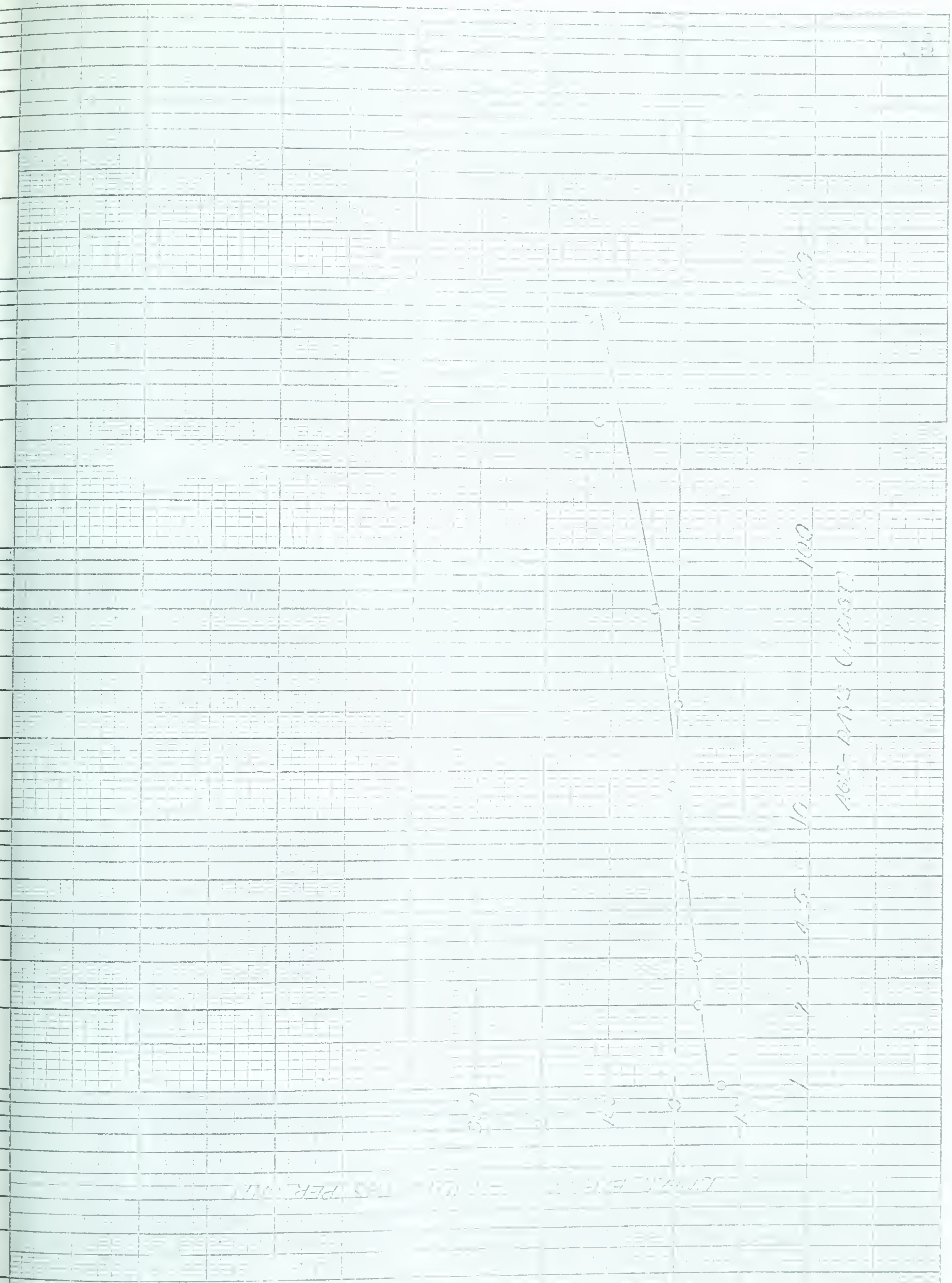


FIGURE NO. 55

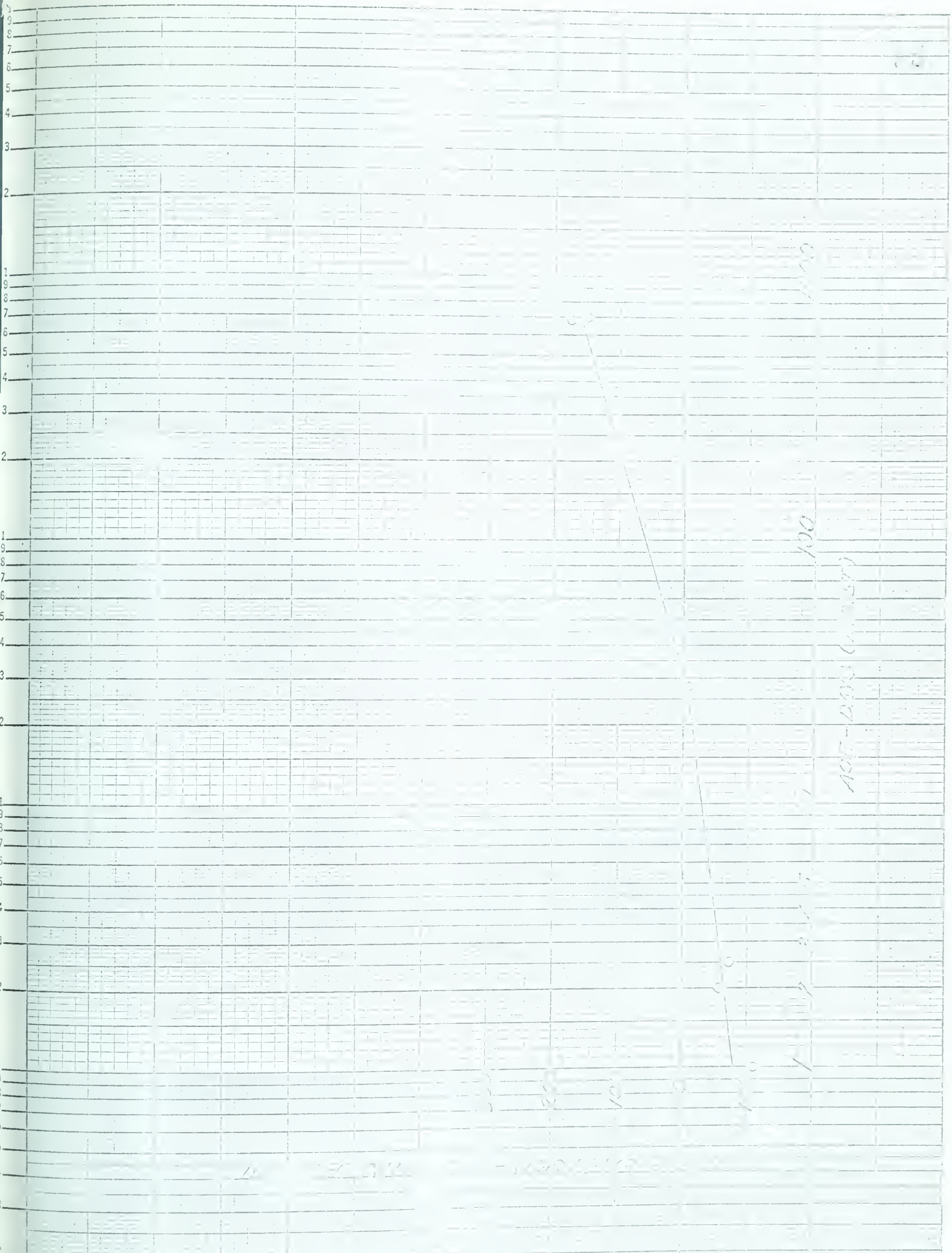


FIGURE NO. 36 LINEAR EXPANSION

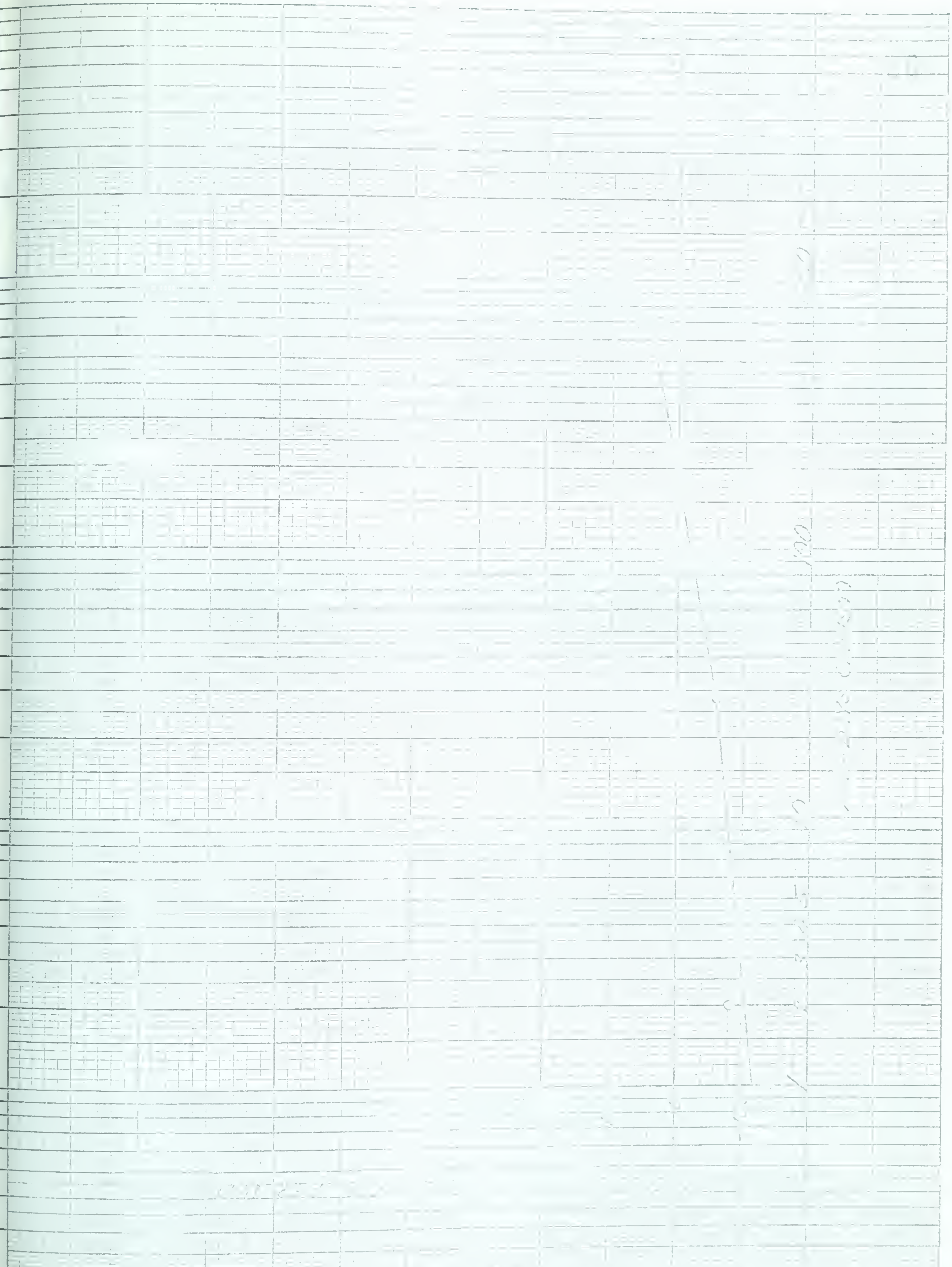


FIGURE NO. 37

[illegible]	38	[illegible]	EXP [illegible]

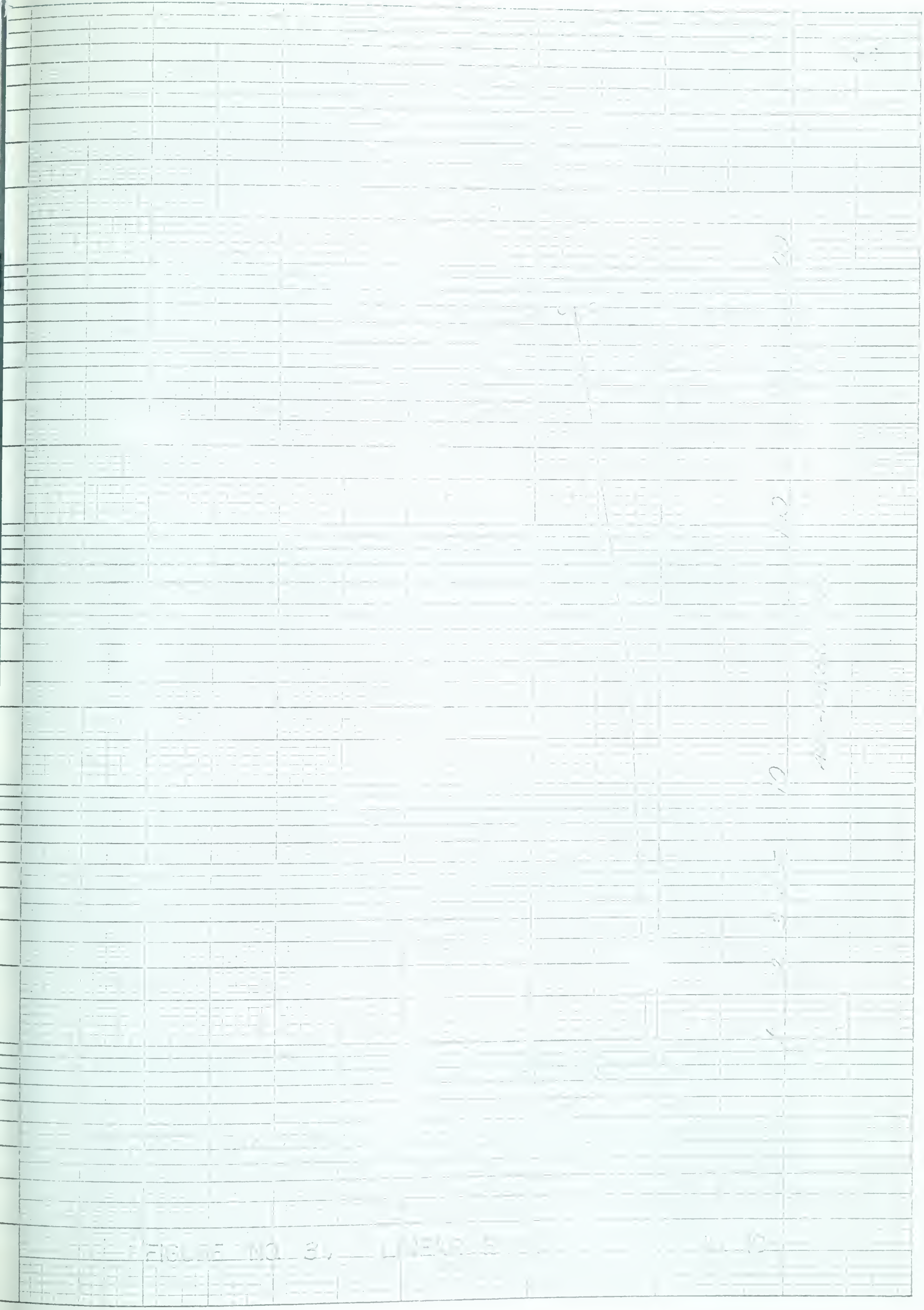


FIGURE NO. 31

[illegible]

this program, that is for the given equipment set-up, materials used, and the fabrication techniques employed. Any attempts to extrapolate these results for other than these given conditions should be made with caution, using sufficient correlated data.

From the analysis of the test results, it is apparent that some of the data is erratic, in that it does not fit in with the general trends. A notable example of this can be found in the monolithic beam flexural strengths for Series II, as shown in FIGURE 22. These erratic results can be explained only by some undetected variation in equipment operation or the shooting technique. Other possibilities are that some of the specimens were jarred and partially fractured in the first few hours after they were shot, or that they contained undetected rebound.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

From the analysis of the test results, certain conclusions appear warranted. It should be remembered however, that the samples were shot under certain specific conditions and any variations in shooting equipment and technique could produce varying results. Some of the general conclusions are as follows:

1. For the conditions investigated, the maximum compressive, flexural, and steel bond strengths for Gun-All are attained with mixes which are of a consistency meeting the field criteria for proper consistency.

2. The range of the flexural strength - compressive strength ratio for shotcrete is closely comparable to the range for normal concrete.

3. With the methods used, the concrete to concrete bond in flexure is on the average two-thirds the strength of monolithic shotcrete.

4. Ultimate reinforcing steel bond strengths of 1000 psi or greater can be attained with normal mixes of shotcrete.

5. For the methods used, there is an indication that the Gunite process gives strength relationships similar to those of the Gun-All process.

6. The expansion of the shotcrete specimens which were subjected to continuously moist conditions for two years was comparable to that which could be expected of regular concrete.

RECOMMENDATIONS FOR FURTHER STUDY

It is recommended that further tests should be conducted to develop improved methods of obtaining representative compressive strength specimens. In order to eliminate the size factor and the l/d ratio factor, it would appear to be feasible and practical to cut 6 in. by 6 in. by 12 in. specimens from a beam in the same way the 4 in. cubes were obtained in this program.

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10. Troxell and Davis "Composition and Properties of Concrete", McGraw-Hill Book Co. Inc. (1956) p. 190.

11. Ibid, p. 189.

12. Gonnerman, H.F. and Shuman, E.C., "Compression, Flexure and Tension Tests of Plain Concrete", Proc. ASTM, Vol. 28 pt. II (1928) pp. 527-573.

13. Troxell and Davis, op. cit., p. 178.

14. Ibid, p. 179.

15. Ibid, p. 239.

APPENDIX A

SAMPLE CALCULATIONS

SAMPLE CALCULATION - density of 6 in. by 12 in. cylinder

Weight of basket & cylinder in water	=	8390 g	$\pm$ 1 g
Weight of basket in water	=	1884 g	$\pm$ 1 g
Weight of cylinder in water	=	6506 g	$\pm$ 2 g
Weight of cylinder in air	=	11849 g	$\pm$ 2 g
Weight of cylinder in water	=	6506 g	$\pm$ 2 g
Weight of water displaced	=	5343 g	$\pm$ 4 g or .08%

$$\text{Density of cylinder} = \frac{11849}{5343} \times 62.4 = 138.4 \text{ lb per cu ft.}$$

$$\pm\ (.08\% + .02\%) = \pm\ .1\% \text{ or } \pm\ 0.1 \text{ lb per cu ft.}$$

SAMPLE CALCULATION - FLEXURAL STRENGTH

$$R = \frac{PL}{bd^2}$$

R = Modulus of Rupture in psi

P = Applied load indicated by testing machine in pounds

L = Span length in inches

b = Average width of specimen in inches

d = Average depth of specimen in inches

Example - beam # 4-2

$$R = \frac{2200 \times 12}{4 \times 4^2}$$

$$R = 410 \text{ psi}$$

APPENDIX B

LINEAR CHANGE DATA

INITIAL READINGS - LINEAR CHANGE SPECIMENS

MIX NO.	AGE AT INITIAL READING -HOURS	NO. 1 INITIAL GAGE READING	NO. 2 INITIAL GAGE READING	MIX TEMP. AT INITIAL READING °F
1	1-1/2	0357	1049	65
2	1-1/2	0540	1235	67
3	2	1175	0772	67
4	3	0815	0919	72
5	4-1/2	0972	1359	69
6	4	0736	1000	69
7	4-1/2	1016	0797	78
8	4	0852	1327	78
9	5	0448	0994	75
10	5	1668	1968	76
11	5	1690	0390	78
12	5	2286	1942	78

				READING NO.1		READING NO. 2		
MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5in. per in.	INCREASE FROM INITIAL READING x10-5 in. per in.	LIN, CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	INCREASE FROM INITIAL READING x10-5 in. per in.	LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
1	6/24	7	-4	7	3	2	-2	5
	1	2	-1	6	5	2	1	30
	2	0	0	1	1	-1	-1	0
	4	12	-7	10	3	10	3	30
	7	10	-6	9	3	10	4	35
	14	10	-6	10	4	11	5	45
	27	11	-7	12	5	12	5	50
	36	13	-8	12	4	12	4	40
	62	8	-5	11	6	12	7	65
	400	9	-5	20	15	21	16	155
	712	5	-3	23	20	24	21	205
	727 0	13	-8	25	17	27	19	180
	Dry- 14	13	-8	24	16	25	17	165
	ing 21	11	-7	21	14	23	16	150
	Time 42	13	-8	-11	-19	-1	-9	-140

NOTE: Figures are positive (Expansion), Unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F^0	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
2	5/24	5	-3	LOOSE		4	1	10
	1	0	0			2	2	20
	2	-2	1			0	1	10
	4	10	-6			10	4	40
	7	8	-5			9	4	40
	14	[illegible]	-5			11	6	60
	27	9	-5			11	6	60
	36	11	-7			10	3	30
	62	6	-4			10	6	60
	400	6	-4			17	13	130
	712	3	-2			20	18	180
	727 0	11	-7			20	13	130
	Dry- 14	11	-7			4	-3	-30
	ing 21	9	-5			-6	-11	-110
	Time 42	11	-7			-32	-37	-370

NOTE: Figures are positive (Expansion), Unless shown as negative (-) (Shrinkage)

				READING NO. 1		READING NO. 2		
MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	INCREASE FROM INITIAL READING x10-5 in. per in.	LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	INCREASE FROM INITIAL READING x10-5 in. per in.	LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
3	4/24	5	-3	1	-2	0	-3	-25
	1	0	0	3	3	1	1	20
	2	-2	1	-4	-3	-4	-3	-30
	4	6	-4	7	3	6	2	25
	7	[illegible]	-5	6	1	5	0	5
	14	[illegible]	-5	8	3	7	2	25
	36	11	-7	7	0	7	0	0
	27	9	-5	9	4	7	2	30
	62	6	-4	8	4	7	3	35
	400	6	-4	16	12	16	12	120
	712	3	-2	20	18	20	18	180
	727 0	11	-7	22	15	22	15	150
	Dry- 14	11	-7	-3	-10	-3	-10	-100
	ing 21	9	-5	-11	-16	-12	-17	-165
	Time 42	11	-7	-21	-28	-22	-29	-285

NOTE: Figures are positive (Expansion), Unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS		TEMP. ABOVE INITIAL F^0	TEMP. CORRECTION $x10^{-5}$ in. per in.	READING NO. 1 INCREASE FROM INITIAL READING $x10^{-5}$ in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. $x10^{-5}$ in. per in.	READING NO. 2 INCREASE FROM INITIAL READING $x10^{-5}$ in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. $x10^{-5}$ in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
4	1		-5	3	4	7	-1	2	45
	2		-7	4	2	6	-3	1	35
	4		5	-3	11	8	12	9	85
	7		3	-2	10	8	10	8	80
	14		3	-2	11	9	12	10	95
	27		4	-2	11	9	15	13	110
	36		6	-4	10	6	12	8	70
	62		1	-1	9	8	11	10	90
	400		1	-1	15	14	19	18	160
	712		-2	1	21	22	22	23	225
	727	0	6	-4	28	24	24	20	220
	Dry-	14	6	-4	2	-2	1	-3	-25
	ing	21	4	-2	-7	-9	-7	-9	-90
	Time	42	6	-4			-18	-22	-220

NOTE: Figures are positive (Expansion), Unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
5	1	-4	2	0	2	0	2	20
	2	-1	1	1	2	3	4	30
	3	8	-5	7	2	9	4	30
	6	6	-4	7	3	10	6	45
	13	6	-4	9	5	12	8	65
	26	7	-4	10	6	14	10	80
	35	9	-5	10	5	13	8	65
	61	4	-2	9	7	12	10	85
	400	4	-2	13	11			110
	711	1	-1	8	7	24	23	150
	720 0	9	-5	6	1	24	19	100
	Dry- 14	9	-5	-14	-19	3	- 2	-105
	ing 21	7	-4	-26	-30	-11	-15	-225
	Time 42	9	-5	-48	-53	-24	-31	-420

NOTE: Figures are positive (Expansion), unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
6	1	-4	2	-8	-6	-10	- 8	- 70
	2	-1	1	-4	-3	- 5	- 4	- 35
	3	8	-5	3	-2	0	- 5	- 35
	6	6	-4	3	-1	2	- 2	- 15
	13	0	-4	5	1	4	0	5
	26	7	-4	6	2	2	- 2	0
	35	9	-5	6	1	5	0	5
	61	4	-2	6	4	5	3	35
	400	4	-2			14	12	120
	711	1	-1			15	14	140
	726 0	9	-5			15	10	100
	Dry- 14	9	-5			-13	-18	-180
	ing 21	7	-4			-25	-29	-290
	Time 42	9	-5			-37	-42	-420

NOTE: Figures are positive (Expansion), unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
7	7/24	2	-1	1	0	0	- 1	- 5
	1	- 9	5	-12	- 7	-20	-15	-110
	2	-10	6	- 8	- 2	-15	- 9	- 55
	2-1/2	0	0	- 4	- 4	-11	-11	- 75
	28	- 5	3	- 1	2	- 6	- 3	- 5
	370	- 5	3	11	14	4	7	105
	678	- 8	5	18	23	7	12	175
	693 0	0	0	19	19	11	11	150
	Dry- 14	0	0	-10	-10	-14	-14	-120
	ing 21	- 2	1	-20	-19	-25	-24	-215
	Time 42	0	0	-29	-29	-32	-32	-305

NOTE: Figures are positive (Expansion), unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
8	6/24	2	-1	- 3	- 4	- 2	- 3	- 35
	1	- 9	5	-19	-14	-19	-14	-140
	2	-10	6	-14	- 8	-14	- 8	- 80
	2-1/2	0	0	- 9	- 9	-14	-14	-115
	28	- 5	3	-10	- 7	- 8	- 5	- 60
	370	- 5	3	- 4	- 1	- 3	0	- 5
	678	- 8	5	1	6			60
	693 0	0	0	5	5	0	0	25
	Dry- 14	0	0	-18	-18	-19	-19	-185
	ing 21	- 2	1	-29	-28	-30	-29	-285
	Time 42	0	0	-40	-40	-41	-41	-405

NOTE: Figures are positive (Expansion), unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
9	9/24	5	-3	4	1	4	1	10
	1	-6	4	- 4	0	- 7	- 3	- 15
	2	-7	4	- 3	1	- 4	0	5
	2-1/2	3	-2	2	0	- 1	- 3	- 15
	28	-2	1	0	1	- 2	- 1	0
	370	-2	1	8	9	5	.6	75
	678	-5	3	8	11	8	11	110
	693 0	3	-2	11	9	10	8	85
	Dry- 14	3	-2	-16	-18	-18	-20	-190
	ing 21	1	-1	-26	-27	-28	-29	-280
	Time 42	3	-2	-37	-39	-40	-42	-405

NOTE: Figures are positive (Expansion), unless shown as negative (-), (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
10	9/24	4	-2	5	3	8	6	45
	1	-7	4	- 4	0	- 1	3	15
	2	-8	5	- 3	2	- 1	4	30
	2-1/2	2	-1	1	0	3	2	10
	23	-3	2	0	2	5	7	45
	370	-3	2	8	10	14	16	130
	678	-6	4	9	13	15	19	160
	693 0	2	-1	8	7	16	15	110
	Dry- 14	2	-1	-17	-18	-14	-15	-165
	ing 21	0	0	-26	-26	-23	-23	-245
	Time 42	2	-1	-34	-35	-32	-33	-340

NOTE: Figures are positive (Expansion), unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION x10-5 in. per in.	READING NO. 1 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 1 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	READING NO. 2 INCREASE FROM INITIAL READING x10-5 in. per in.	READING NO. 2 LIN. CHANGE CORRECTED FOR TEMP. x10-5 in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
11	8/24	2	-1	15	14	14	13	135
	1	- 9	5	4	9	1	6	75
	2	-10	6	5	11	2	8	95
	2-1/2	0	0	9	9	[illegible]	[illegible]	85
	28	- 5	3	10	13	10	13	130
	370	- 5	3	18	21	21	24	225
	678	- 6	5			26	31	310
	693 0	0	0			30	30	300
	Dry- 14	0	0			8	[illegible]	80
	ing 21	- 2	1			- 3	- 2	- 20
	Time 42	0	0			-12	-12	-120

NOTE: Figures are positive (Expansion), unless shown as negative (-) (Shrinkage)

MIX NO.	AGE DAYS	TEMP. ABOVE INITIAL F°	TEMP. CORRECTION $x10^{-5}$ in. per in.	READING NO. 1: INCREASE FROM INITIAL READING $x10^{-5}$ in. per in.	READING NO. 1: LIN.CHANGE CORRECTED FOR TEMP. $x10^{-5}$ in. per in.	READING NO. 2: INCREASE FROM INITIAL READING $x10^{-5}$ in. per in.	READING NO. 2: LIN.CHANGE CORRECTED FOR TEMP. $x10^{-5}$ in. per in.	AVERAGE LINEAR CHANGE MILLIONTHS
12	8/24	2	-1	11	10	9	8	90
	1	- 9	5	- 3	2	-2	3	25
	2	-10	6	1	7	1	7	70
	2-1/2	0	0	5	5	5	5	50
	28	- 5	3	6	9	7	10	95
	370	- 5	3	10	13			130

NOTE: Figures are positive (Expansion), unless shown as negative (-) (Shrinkage)

APPENDIX C

PRELIMINARY DRYING SHRINKAGE DATA

Subsequent to obtaining the data for linear expansion under moist conditions, as was presented in the body of this report, the linear change specimens were subjected to drying conditions. The drying shrinkage data obtained up to the time of writing is included in this appendix.

This data does not pertain to the body of this report. It is included here as preliminary data for possible future study of the ultimate shrinkage of these specimens.

FIGURE NO. C1 LINEAR SHRINKAGE

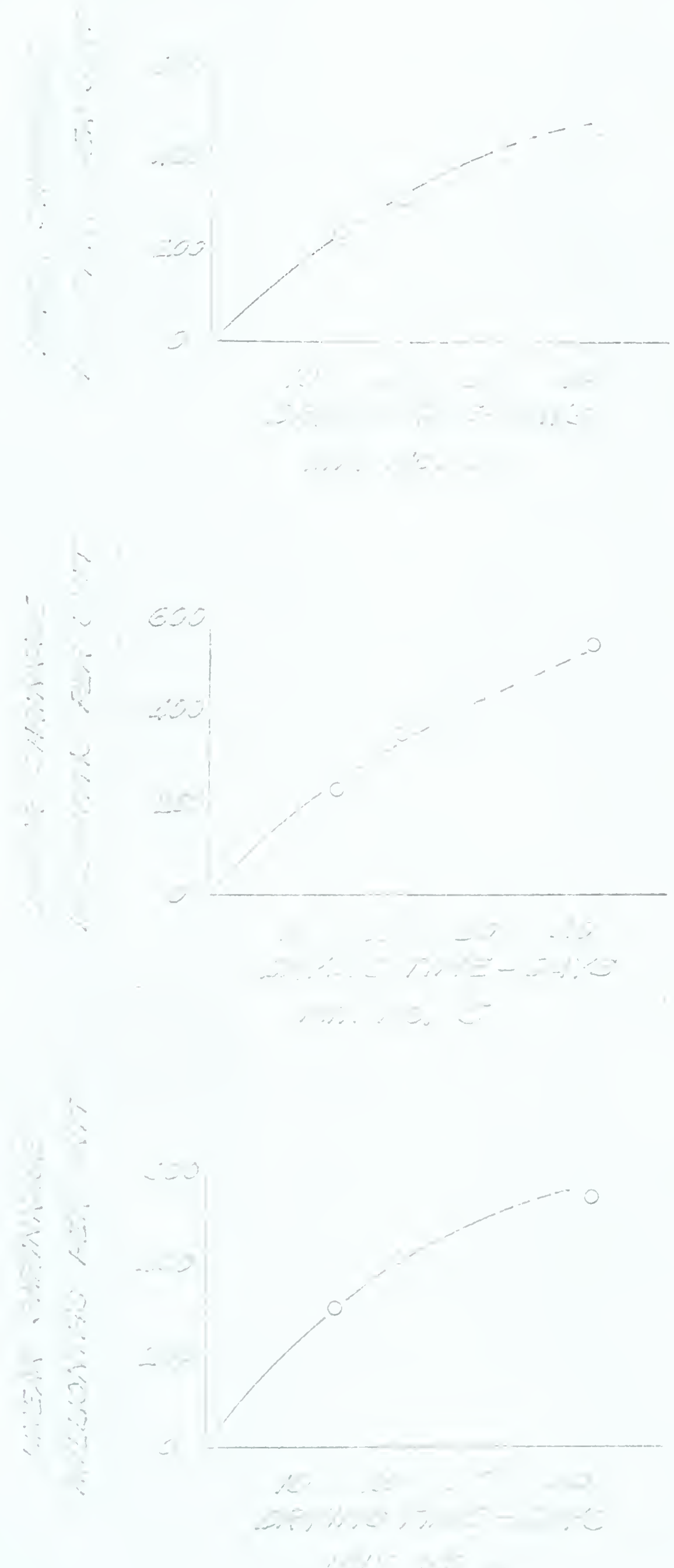

FIGURE NO. C2 LINEAR SHRINKAGE

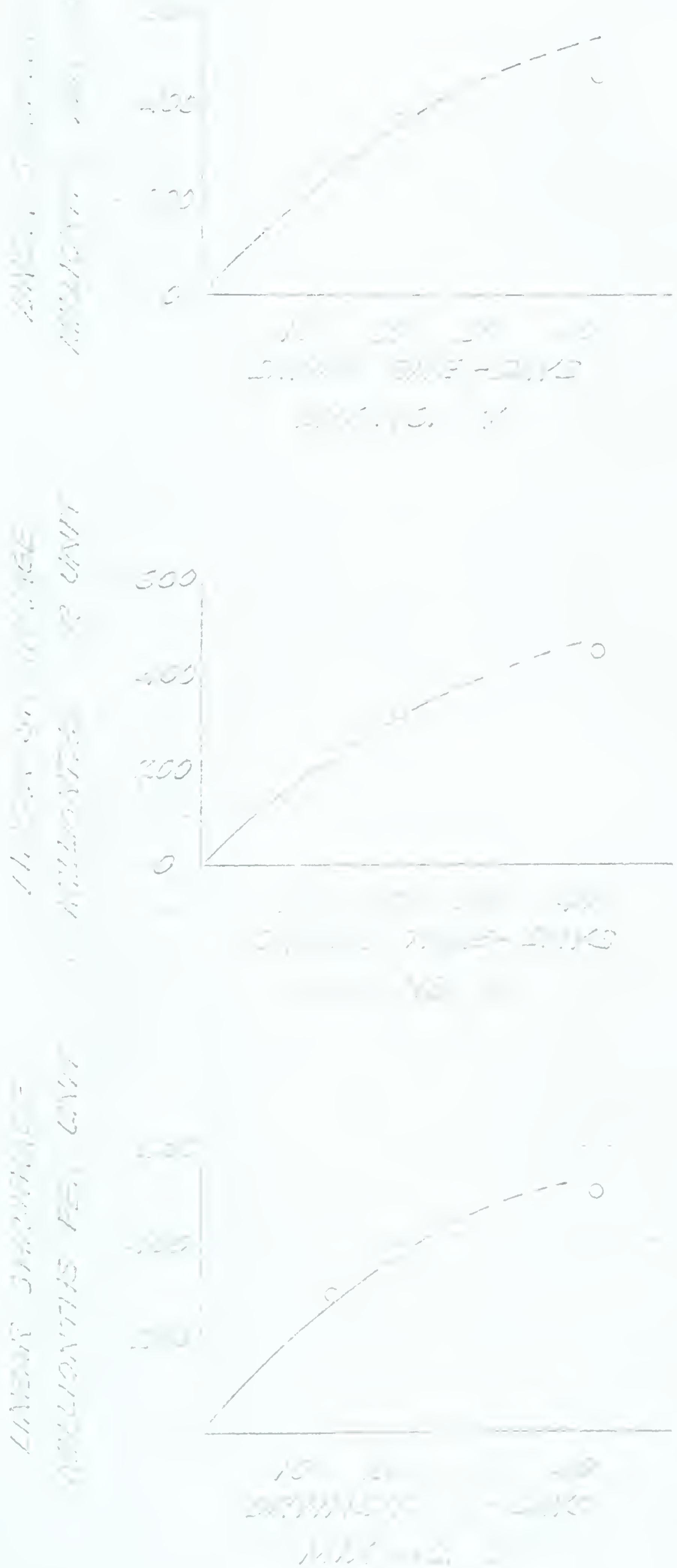

FIGURE NO. C5 LINEAR SHRINKAGE

FIGURE NO.